A history of Science and Technology. 1

ANCIENT TIMES TO THE SEVENTEENTH CENTURY

R. J. FORBES AND E. J. DIJKSTERHUIS

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Both the authors of this work are Dutch professors of the history of science – E. J. Dijksterhuis (left) at the University of Leyden, and R. J. Forbes at the University of Amsterdam.

The former was born at Tilburg, in Holland, in 1892, and graduated in mathematics and physics, which he taught for many years in the high school at Tilburg. Early examinations had forced on him a study of Latin and Greek and this engendered in him an interest in the history of his subjects. Over the years he has published works on the history of mechanics, on Euclid, on Simon Stevin (on whom he is perhaps the principal authority), and, notably, on Archimedes.

R. J. Forbes was born in Breda in 1900 and graduated as a chemical engineer. Since 1923 he has had a distinguished and uninterrupted career with the Royal Dutch Shell Group, both in their research laboratories and in refineries in the East Indies. He was always interested in archaeology and museum collections and has published books and papers in several languages on the history of metallurgy, petroleum, roadbuilding, technology, food, distillation, and even alchemy. These have given him an international reputation as a historian of man's exploitation of the wealth of nature.

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A HISTORY OF SCIENCE AND TECHNOLOGY

VOLUME 1

R. J. FORBES AND E. J. DIJKSTERHUIS

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'Nature Obeyed and Conquered'

1

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E. J. Dijksterhuis

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Introduction

THE sub-title of this book is taken from one of the many brilliant aphorisms in which Francis Bacon expressed his ideas on scientific method and purpose: *Natura non nisi parendo vincitur* (Nature can be conquered only by obeying her: *Novum Organum* I, 3).

At the present time the correctness of this notion is obvious every day to everyone who does not go through life with his eyes shut: man shows himself able to conquer nature, to control her, and to make use of her, but in order to do so he must obey her laws and he can do this only by first learning about those laws through his own researches. In plain words: technology must have science as its basis; science makes technology possible.

Contemporary man, who has grown up in a society in which scientifically-based technology forms an essential element, is inclined to look upon the close relationship between these two aspects of human existence as self-evident, just as he generally accepts without question the very existence of those aspects. This may be an understandable attitude, but it is none the less to be deplored. It creates an atmosphere of thoughtless enjoyment, a lack of appreciation for the stupendous intellectual effort which scientists and technologists have made down the centuries in order to reach the present-day level and which they are still making in order to reach yet higher levels.

There is only one remedy for this undesirable attitude: the study of history. Not until people have learnt to see how our present knowledge and ability has grown from very modest beginnings, as a result of indefatigable collaboration between many minds and ceaseless collective development of what has once been achieved, will they be able to appreciate it fully and learn to use it with respectful gratitude.

This book is intended to make a modest contribution towards realizing this aim by broadly outlining the development of the wealth that Western culture has acquired in the field of science

and technology from the earliest times up to the beginning of the close collaboration between them.

The subject thus envisaged is so vast and complicated that the task of giving an account of it in a small book of limited compass made a highly selective treatment imperative. The authors were therefore obliged to start by including only the science of inorganic matter and to omit biology and medicine entirely. Even then, it was not possible for them to be comprehensive or thorough in their treatment of the material. Their aim has therefore been merely to give not too incomplete an impression of the historical development of the subjects which *have* been included, in the hope of thereby arousing interest in the history of science in general. Any accusations of incompleteness and superficiality which may be addressed to them will be accepted uncomplainingly. The detailed bibliographies at the end of each volume will, however, point the way to more thoroughgoing studies for those who feel the need for them.

However closely linked science and technology may be today, they have developed historically along virtually separate paths. For a long time science remained indifferent to the practical application of its conclusions; for a long time technology had to do without its help and more than once deliberately scorned such help just when it could have derived benefit from it. The possibility and desirability of collaboration between the two was first realized and advocated at the beginning of the seventeenth century by a few individuals – for example, Francis Bacon in England, René Descartes in France, and Simon Stevin in the Netherlands – but it was not until the eighteenth century that it began to be put into practice. This historical course of events is reflected in the plan of this book. It has been written by two authors, who have divided the material between them, one looking after the chapters on physics and astronomy and their mathematical or philosophical bases, the other dealing with the chapters on technology and the subject which has always been closely connected with it, chemistry.

Each author carries responsibility only for what he has written, namely E. J. Dijksterhuis for Chapters 2, 3, 6, 7, 9–12, 14, 15,

17–19, 21–23, and R. J. Forbes for Chapters 1, 4, 5, 8, 13, 16, 20, 24–26.

A basic difficulty which confronts the writer of a book on the history of science lies in limiting the material as it approaches the present day. Many readers expect that a work on the historical development of a science will deal with its growth up to very recent times and that it will be a sort of textbook of the present-day science on an historical basis. That may seem attractive, but it is a fundamental misconception. The historical method is different from the systematic method. Above all it demands the ability to view with detachment the events one has to deal with. In view of the stupendous proportions assumed by every branch of science today, such an historically constructed textbook or manual would also be quite impracticable.

This means, for one thing, that the whole of what is known as modern science, which may be defined as everything that has occurred since 1900, has had to be excluded. The same is true of the close link between science and technology, which in the main has also been established for the first time in the twentieth century.

This would in any case have been impossible, because the demands which have to be made on the mathematical training of the reader in dealing with a given period differ greatly for different subjects, whereas in writing the work it has been assumed, as a general principle, that in this respect no more should be required of the reader than is to be expected at undergraduate level. In a sound exposé of the history of science and technology, the information given should really be continually substantiated by means of references. But in view of the book's limited scope and because of their desire to make it suitable for the general reader without a specifically historical training, the authors have felt obliged to dispense with references and footnotes. Anyone who refers to the works mentioned in the bibliography will, of course, find full documentation there.

CHAPTER 1

The Beginnings

It is vain to speculate on the question where and when science started. It is true that the paintings in prehistoric caves not only truly and faithfully depict plants, animals, and the actions of man but also natural phenomena such as constellations of stars observed by primitive men. Archaeologists have found pebbles painted with what may be a kind of primitive script and numerals, but we cannot read them. We can only conclude from the remains, which date from a period many centuries after mankind appeared on earth, that at a very early date man had begun to observe and record certain natural phenomena. Whether and how he tried to interpret them is beyond our ken. We have some inkling of the workings of the primitive mind from the studies of ethnologists describing primitive tribes still to be found in this modern world in certain remote corners of the earth, but we must be forewarned not to trust such evidence too much because some of these tribes later proved to be degenerates rather than primitives. The only thing we know for certain is that the conclusions drawn from these observations of natural phenomena form part and parcel of the world-picture of such primitive peoples. They are embedded in the dominant religious and philosophical tenets of the tribe and are not treated as a separate field of thought such as science is for us.

EARLY SCIENCE

When in the fourth millennium B.C. writing was invented in the Near East in Mesopotamia and spread to Egypt a few centuries later we get a firmer grip on the part which scientific observations and data played in these early civilizations. Cuneiform tablets and papyri covered with hieroglyphs tell us of the first steps of the early scientists. Gradually more and more texts, notably those of a

mathematical and astronomical nature, appeared as the centuries rolled by.

In order to understand what these scientists did we must remember how a modern scientist works. When he has recognized a problem and has decided whether his objective will be to formulate the general rule governing the phenomenon or to get to the bottom of it, he collects the relevant information and data. He then formulates a working hypothesis, draws deductions from this hypothesis, and puts these deductions to the test by trial and experiments. Depending on the outcome of these experiments he accepts the working hypothesis or modifies or even discards it. Other scientists will then confirm and use this evidence.

As far as we know, the pre-classical scientist never went so far as to conduct experiments. There are a few rare instances of experiments of pre-classical date. Thus, an Egyptian nobleman prided himself on the fact that he constructed a graduated 'water-clock' for his king, that is he constructed a vessel in the shape of a truncated cone with a little hole near the bottom. He then graduated the interior with marks which allowed the observer to read the intervals of time elapsing as the water level dropped from mark to mark. However, this experiment was not conducted to prove or support a hypothesis.

Writing, it seems, was invented for the purpose of keeping the records of the temples of early Mesopotamia and to register the grain, sheep, and other tribute which was delivered to its storehouses or distributed. At an early date we find lists of plants, animals, stones, and stars arranged in groups of seemingly related objects. These 'onomastica', found both in Mesopotamia and Egypt, are the first attempts at classification of carefully observed natural objects. They are classified by recording their characteristics (real or imagined) and grouping together such objects or living beings as had certain characteristics in common and therefore seemed related in some way.

In certain texts of ancient Sumer (Lower Mesopotamia) this relation is stressed by the terminology used. All the members of one 'species' are denoted by one general term such as 'white, black, or iron stone', 'wood', 'vessel', to which a suffix or prefix

is added describing a special characteristic of the individual member of the 'species', such as colour, hardness, etc. The nomenclature thus obtained resembles that of modern organic chemistry which, for instance, distinguishes such individual alcohols as methyl alcohol, ethyl alcohol, and amyl alcohol. The individual properties such as colour and hardness in the Sumerian lists of minerals thus enable us to identify nearly all the 140 minerals mentioned. This classification of natural objects and phenomena may be regarded as the earliest attempt at scientific reasoning and in fact as the first phase of true science.

On the other hand, the value of these classified lists should not be overestimated. Although no less that eight per cent of the library of the Assyrian king Assurbanipal consisted of such lists, they classify not only natural objects, but also gods, demons, towns, countries, rivers, and professions or titles of officials. They seem to have been used in the temple schools by the scribes to instruct their pupils in the art of writing, and in later periods they served to teach Assyrians and Babylonians Sumerian (a dead language by that time but still the 'Latin' of their religious literature) or for bilingual dictionaries with philological footnotes. Still, these lists show how carefully and accurately natural objects were observed, what properties were already known, and how the experience of the scribes and the craftsmen was building up a 'system of nature'.

Ancient science, as found in the earliest mathematical and astronomical documents, was taught by the priests and scribes in the temple schools, the only schools then available even to those who did not become professional priests but held posts in the government and the army. Science was not a subject of its own; it consisted of a series of computational rules and methods of calculation used in commerce and trade, engineering, and taxation, or the prediction of astronomical phenomena and determining the calendar or religious festivals. Science, if we can call it such, only formed part of religious and philosophical wisdom. It did not construct a world-picture of its own built solely on the observations of natural phenomena and resting on certain supposed or established 'laws of nature'. Such a concept was totally foreign to

pre-classical civilization; the world of the senses still formed part of the world as created by the gods 'in the beginning'.

WEIGHTS, MEASURES, AND NUMERALS

Ancient mathematics was primarily a set of methods and rules for practical use. The Greek 'arithmein' (to count) and the Latin 'calculare' (to calculate; from 'calculus': small pebble) demonstrate the original daily use of arithmetic from which the more general science of algebra developed. In the same way the Greek 'geometrein' (to measure land) indicates that geometry was originally used to determine the area of fields and plots for registration or taxation purposes. Ancient Egyptian and Mesopotamian texts and reliefs often show officials with their servants at work with a surveyor's chain.

When the records begin to demonstrate the application of mathematics to daily life, civilization was already far advanced in the river valleys of the Nile, the Euphrates and the Tigris, and the Indus. Perhaps writing appears somewhat later in the story of Egypt than in Mesopotamia, but in both cases we find a country predominantly inhabited by farmers, ruled by a government mainly concentrated in towns and with full authority over a well-established trade and industry supported by merchants and craftsmen. Standards to express measures, quantities, and weights are already fully developed. In most countries there were several systems for expressing weights, one used for bulky merchandise and one or more troy standards for gold and silver, because commerce took the form of barter, the difference in value being paid in weights of gold, silver, or copper.

The units of measurement were taken from the human body, the span, the finger, the palm, the forearm, and the foot serving as units. The most popular of these was based on the length of the forearm, usually called ell or cubit. Four ells made the fathom. Such standards were closely bound up with the development of the textile industry and trade and clung to it for many centuries.

In many cases we can no longer trace the origin of such sys-

tems. In ancient China the standards of measurement and weight seem to have been based on the dimensions and weight of the red millet seed. In Mesopotamia and the western Semitic world the talent–mina–shekel system of weights (so familiar from the Bible) may go back to the weight of the grain of barley, so effectively standardized by Nature; the system of measures in this region is also said to be based on the length of the grain of barley. Whether this will prove to be true or not, there is the undoubted fact that early in the history of the ancient Near East there was a great need for methods of converting weights and measures into one another, as each region and each city-state tended to have its own standard, sometimes differing only little from that of its neighbours. Trade and government were active in helping to create the simple calculation rules and methods which we call arithmetic.

One of the most important factors in the development of mathematics was the choice of the symbols to denote numerals. A clumsy form of notation or the lack of clear symbols could and did impede the development of this science. The oldest form of writing was based on the pictorial representation of ideas; the earliest number signs were groupings of strokes and tens. Gradually a new way developed to denote higher units (in our decimal system hundreds, thousands, etc.). The Mesopotamian scribes chose 60 as their unit. This choice may have been determined by the fact that in their system of weights the mina had 60 shekels.

Most important, however, was not this choice of unit (60) but the introduction of the place-value system as is now used in our figures, where the place of the digit in the numeral shows us at the first glance whether it denotes the units, tens, hundreds, etc. Hence the Babylonian scribes would write  (which we usually transcribe as 1,23) meaning $1(\times 60) + 23$ or 83 in our system of notation. This choice of a sexagesimal system (based on 60) and a place-value notation determined the rapid growth of Babylonian mathematics. It did not require the variety of symbols for units of a different order or for various fractions as introduced by the Egyptians and it increased the readability of mathematical texts.

BABYLONIAN MATHEMATICS

Our knowledge of the development of Mesopotamian mathematics is still fragmentary. We know that the oldest inhabitants of the Land of the Two Rivers, the Sumerians, must have developed mathematics beyond the stage of simple arithmetic by adopting well-chosen symbols for a sexagesimal system and the place-value system. Invented in the early days as a tool for the extensive temple administration of the different city-states, collecting and distributing natural products and manufactured goods belonging to the estates of the gods, mathematics was soon taught in the schools, and fragments of early texts show that this discipline was believed to be indispensable.

Our main body of cuneiform mathematical tablets dates back to the old Babylonian period (1800–1500 B.C.) and to the Hellenistic (Seleucid) period (300–0 B.C.). These collections of texts are of two types. The 'table texts' are of immediate practical use. These tablets contain tables to facilitate the conversion of larger units into smaller ones and vice versa. Many of these tables consist of multiplication tables, some of which also contain tables of squares and cubes enabling square and cube roots to be drawn and cubic equations to be solved. There are many tables of inverses or reciprocals, for the division of say $a:b$ was carried out by multiplying a by $\frac{1}{b}$. In the sexagesimal system used in ancient Mesopotamia many such reciprocals could be expressed as finite sexagesimal fractions; thus dividing by 12 was resolved into multiplication by 5 followed by the (easy) division by 60. These tables probably served for instruction at the temple schools. Many of them contain such rather unreal 'sums' as we still do in elementary schools, but they also deal with problems of weaving, sheep, grain, precious metals, and inheritance, therefore with the problems of daily life, commerce, and engineering.

The second group, the so-called 'problem texts', are mostly of a purely algebraic character, even when dealing with geometric problems. Often they define the product of two unknowns as an

'area' but this seemingly geometrical formulation is simply a condensed form of the expression of linear or quadratic equations (or those equations which are reducible to quadratic forms). Numerical methods are used to supplement general algebraic procedures. Geometrical problems, as far as they were understood, were solved algebraically if possible. They must have served as mathematical excercises, for some tablets contain algebraic equations of the fourth and the sixth degree, formulae of areas of regular polygons, or formations of Pythagorean triplets of integers, which are all of purely mathematical interest. We have no indication that there was any attempt at real pure mathematics, but at a very early date the Assyrians and Babylonians certainly developed practical mathematical methods to approximate and calculate the fairly complicated astronomical phenomena such as the position of certain planets in the sky in the near future, and this enabled them to get a grip on astronomy much earlier than any other Near-Eastern civilization. By 300 B.C. they fully applied their mathematics to such astronomical calculations, and from that date onwards theoretical astronomy was for many a century the only field in which mathematics were used to understand and describe the natural phenomena.

EGYPTIAN MATHEMATICS

We have even fewer remains of Egyptian mathematical papyri, which, with the exception of the Rhind and the Moscow papyri, date from a late period.

In the Nile valley mathematics never developed further than the early stage of computations for certain practical problems. The choice of symbols for the numerals fell on a clumsy system in which each higher unit of the decimal system had its special symbol. It had many analogies with that of the Romans, which was likewise not very suitable for intricate calculations. Although the Egyptians developed better formulae for the computation of triangular, rectangular, and trapezoidal areas and volumes than the Babylonians, they were hampered by the variety of measures of area and capacity in use in their country. The

mathematical problems centre around the calculation of the volume of ramps for the construction of buildings and pyramids, the division of quantities of beer and bread and the like. Such calculations were of course needed in daily life, but, though the Egyptians had considerably more engineering skill than the inhabitants of Mesopotamia and constructed large works in natural stone, we must remember that their mathematics served to solve only minor problems of transport, etc., but never allowed them to apply mathematics to construction problems, the science of statical mechanics and the strength of materials of course being far beyond their reach.

Egyptian arithmetic was restricted to the simplest methods of multiplication and division by 'duplication' and 'halving'. If for instance 12 had to be multiplied by 5, the Egyptian would start writing $1 \times 12 = 12$, then 'doubling' $2 \times 12 = 24$, then 'doubling' again $4 \times 12 = 48$ and as $1 + 4 = 5$, therefore 5×12 would be $12 + 48 = 60$. Division was considered to be a kind of multiplication, but it was formulated inversely, i.e. it was stated by what figure the divisor should be multiplied to obtain the figure to be divided! Their way of writing fractions complicated calculations very much. The Egyptian had special symbols for $\frac{1}{2}$, $\frac{2}{3}$, and $\frac{3}{4}$; in the case of corn measures he used another set of symbols for $\frac{1}{2}$, $\frac{1}{4}$, 1/16, 1/32, and 1/64. In the case of other fractions he could only write fractions with unity as the numerator. Hence he could write 1/5 as 'part 5' (the fifth part), but for him such a thing as 2/5 was nonsense, for there was only one 'fifth part'. Hence he had special tables to help him dissolve 2/5 into '1/3 + 1/15'. Calculations with fractions could only be executed by special techniques which still survive in papyri of the Greco-Roman period and in Latin treatises of surveying; they were still taught in ancient Greece as 'Egyptian method of computation'.

EGYPTIAN ASTRONOMY

As in the case of mathematics, the importance of the Egyptian contribution to early astronomy was greatly exaggerated by the Greeks. In fact Egyptian astronomy never developed beyond the

preliminary stage until it came into contact with Babylonian astronomy in the Hellenistic period (300–0 B.C.).

We have only two old Egyptian Demotic papyri based on originals dealing with astronomy, but more material dating from the Hellenistic period and written in Demotic or Coptic. The oldest astronomical documents are the so-called diagonal calendars painted on the lids of coffins dating back to the Middle Kingdom period (2000–1600 B.C.) and pictures of configurations of stars on the ceilings of later New Kingdom tombs.

Both in Egypt and in Mesopotamia the heavens were observed at an early date, stars were named, configurations of stars recognized and dedicated to gods or supernatural powers. In Mesopotamia certain series of such configurations were arranged in lists wrongly called 'zodiacs' showing the sequence in which they were characteristic of the night-sky in certain parts of the country. However, this does not yet constitute astronomy. Such observations had great importance in ancient life, as religious festivals and indeed many events in political and economic life were believed to depend on certain celestial phenomena and configurations.

True astronomy only began with the attempts at a crude prediction of such phenomena as the phases of the moon, that is with the introduction of the calendar.

The early calendars were based on short-range predictions of the return of certain celestial phenomena such as the waxing or the waning of the moon. Both Egypt and Mesopotamia had lunar calendars, that of Egypt beginning with the invisibility in the morning of the waning moon, that of Mesopotamia being based on the reappearance of the crescent moon in the early evening. Practical observation over a series of years soon led to the discovery that the lunar 'month' embraced either 29 or sometimes 30 solar days, but the early lunar calendar could not yet cope quite successfully with the complicated succession of hollow and full lunar months. Only by 300 B.C. did the Babylonians succeed in establishing a fairly good cycle of lunar months by mathematical methods applied to the many series of observational data.

In addition to the lunar calendar Egypt introduced at an early

date a civil calendar for economic life, of 12 months of 30 days each. With 5 extra intercalary days it formed the Egyptian civil year of 365 days, an important invention. It was soon found that the solar year was 365 days and 6 hours, and we now add a day every four years to make the civil year coincide with the solar year. The Egyptians also had an agricultural calendar consisting of three seasons connected with the rise of the Nile, the inundation year coinciding with the civil year.

Of course the problem of connecting the civil calendar with the religious lunar calendar arose early in Egypt. This was solved by a 25-year cycle consisting of 16 small years of 12 lunar months. This cycle was well known to Greek astronomers as a convenient basis for the computation of lunar phenomena in Egyptian years.

In the Egyptian agricultural calendar the stars also played a prominent part. Observation over many centuries taught that the heliacal rising (the moment of the first visibility of a star in the region of the sun) of such important stars as Sirius could be related to the civil calendar. A system arose in which a specific star was connected with each of the three decades of the civil month, and hence we find lists of such 'decans' in early coffins and tombs.

The Egyptian priests and 'hour-watchers' observed the transits of these decans (and other stars) with the help of a simple plumb line (the 'merkhet', Plate 2a) and a water-clock. By 2500 B.C. successive risings of such stars led to the use of a star-clock, dividing the period from dusk to dawn into 'twelve hours of the night'. Egyptian sense of symmetry turned this into the division of the day into 24 hours, which we still use. When in Hellenistic times Babylonian astronomy came to Egypt, this Egyptian 24-hour day came to be subdivided into 60 minutes per hour and the unequal hours of the early astronomers (which varied with the length of the day and the night according to the seasons) were replaced by hours of equal length. During daytime the passage of time was roughly estimated with the help of shadow-clocks.

BABYLONIAN ASTRONOMY

Egyptian astronomy never went beyond this stage of the creation of a reasonably acceptable calendar system and a lunar–solar cycle of years. The Babylonian astronomers proceeded beyond this point, though they did not possess any better instruments than the Egyptians. They too originally had a system of 'hours of the night' of varying length as the seasons succeeded each other, and their day was divided into six parts. The distance between celestial bodies was expressed in terrestrial distances transferred to the sky, and by thus using their standard of length the Babylonians came to divide the circle into six equal parts, a procedure that has left its traces in our geometry and trigonometry.

Babylonian astronomy achieved much greater accuracy for its methods of prediction by the application of mathematical methods to the observations. This application certainly began about 500 B.C. and was in full swing by 300 B.C. This is demonstrated by several hundreds of astronomical tablets dating mostly from 240–40 B.C. and showing the high theoretical level attained. About 380 B.C. the Babylonian astronomers found a practical relation between the lunar and the solar calendar, consisting of a 19-year cycle comprising seven years of 13 lunar months and twelve of 12 months. This cycle was also proposed at Athens by Meton in the year 432 B.C. and hence we know it as the Metonic cycle, which later became important as the means of calculating the date of Easter Sunday in the Christian calendar.

PREHISTORIC TECHNOLOGY

The story of man on earth must have had hardly begun when he started fashioning tools and objects, as these are found along with his remains. Very early therefore he showed himself to be *homo faber*, Man the Maker. Life itself imposed on him the necessity of solving such problems as feeding, warming, and protecting himself and his family. Legends and myths of many peoples have rightly stressed the importance of his first conquest, the making of

a fire to heat and to protect him and to widen the range of natural products to be used as food, many of which would be impalatable unless properly cooked. Prometheus, who snatched the fire from Heaven, was the pioneer of crafts and technology. Most of the later crafts and techniques sprang from the kitchen fire and the possibilities of using heat to transform natural substances into useful products.

Hence man not only made many discoveries of useful animals, plants, and stones or other materials already available in nature but also sharpened his intellect by observing their characteristics and properties and employing them together with the forces available in nature to produce new objects and commodities, his own inventions. We can barely follow this trial of discoveries and inventions from the relics brought to light by the archaeologists, for the remains of man and his belongings in different parts of the world have been subjected to so many varieties of climatic conditions that we only have the pitiful relics of a few instants of the story which lasted for many centuries. Our knowledge of prehistoric man will therefore remain fragmentary, for we are also handicapped by the lack of any written evidence which represents his thoughts and beliefs, his achievements, and his dreams.

Still this should not lead us to underestimate his technical capacities. We know that in the Old Stone Age he began to shape tools from stones such as flint. By chipping away flakes until a useful core remained he fashioned such tools as the axe, which allowed him to clear a space in the dense forest and to start on the beginnings of the carpenter's craft. By directing his chipping of flint towards the production of useful flakes he produced different types of knives, saws, and chisels which allowed him to fleece and skin animals of the steppe and furnished him with useful weapons for the chase. Nor should we underestimate the usefulness of such tools. Modern experts, comparing the cutting angle and shape of such prehistoric tools with modern ones, find that they do not differ in principle and that many a prehistoric tool would be as efficient and economic as a modern tool if guided by a skilled hand. In the New Stone Age man learned to polish

harder stones, such as granite, and developed further shapes of useful stone tools to complete a tool chest which would have compared favourably with that of any good craftsman of a century ago, before the advent of modern machinery.

Hence Stone Age man slowly learned to work stone into implements and tools and later into domestic utensils, his techniques gradually acquiring a high efficiency. He also worked bone, ivory, and wood, but here his techniques were confined to cutting, chopping, adzing, scraping, and sawing, and the working of these materials with stone tools remained a comparatively simple procedure without significant changes throughout prehistory.

Not only did he master and elaborate the techniques of foraging, hunting, and fishing, but he also learned to prepare food by cooking it in containers with the help of preheated stones and later in the fireproof pottery vessels he made by hand. Grilling, frying, and other kitchen techniques held no mysteries for him and with the help of his fire he could not only roast his corn in order to grind it more efficiently, but could preserve his food by drying and smoking, and later also by pickling it with salt. This preservation of food was a most important means to make him independent of the vagaries of climate, the varying harvests, and the cold, unproductive winter.

The need of proper shelter and clothing taught him new crafts. Not only did he live in caves and natural shelters, but he started out to build himself wooden huts, and having mastered the art of basketry, he could build a wattle framework to be plastered with mud and clay. He built elaborate pile-dwellings off the shores of inland lakes to protect himself from attacks by man and beast. He learned to use vegetable fibres such as nettles and flax, or animal hair such as wool; he cleansed, spun, and wove them into clothes, mats, and blankets. He learned to roll and compress animal hair into felt, which served for tents, shoes, and clothes, and he was able to convert a hide into leather. He knew how to extract vegetable dyes from several plants, and mineral pigments mixed with animal fat served him when painting his religious and magical scenes on the walls of caves illuminated by simple stone

lamps in which a wick fed with fats and oils provided the flame.

Indeed by the dawn of history he had mastered the principal operations in many fields such as textiles and leather, and the subsequent history of these techniques is hardly more than that of the mechanization of these principal operations originally carried out by hand.

PRE-CLASSICAL TECHNOLOGY

Shortly before written documents began to supplement the evidence provided by the archaeologist (about 3000 B.C.) a social change took place, which Gordon Childe has correctly called the 'urban revolution'. Gradually the shores of the Mediterranean and parts of Europe, Africa, and Asia became the home of sedentary peasant populations, and the hunter and nomad receded to the fringes of thjs oikoumene. In the Fertile Crescent stretching from Egypt to the Persian Gulf very early farming settlements have been found at Jarmo and other sites, whose economy centred on wheat, barley, sheep, goats, and cattle. At Jericho there was a walled settlement dating back to 6000 B.C., even before pottery was known. Before the dawn of history larger units were formed in the valleys of the Nile, the Two Rivers, and the Indus which we know as the early empires of the East. These early empires were based on agriculture; their centres were formed by cities in which the craftsmen, the merchants, and the governing classes resided. Such crafts were frequently carried out in the temples and government workshops, where the prime materials were assembled as tribute or taxes in kind and worked by the specialists attached to such establishments. If in many cases this led to certain associations or guilds, we must not forget that many crafts were still carried out in the homes of the farmers and townsmen themselves. If we read about specialists and skilled foremen being trained in the schools, this usually refers to officials, who were responsible for public works and government expeditions or undertakings and hardly represents anything like the technical education we know. Still, the lists of craftsmen and government officials show that a certain amount of specialization had already

taken place in these early cities and that such crafts as metallurgy were carried out as a full-time job, the smith selling his products to the townsmen and farmers in order to provide for his daily needs.

The early empires coincide with what the archaeologist calls the Bronze Age, when metallurgy had been introduced. After primitive man had worked some native metals like gold and copper as he would any other kind of 'stone', he learned to smelt ores with charcoal in crucibles and furnaces to copper and soon afterwards to alloys of copper. The latter were not yet made by alloying two or more metals as such, but copper ores or crude copper were 'refined' with ores containing other metals such as tin, antimony, or arsenic and when smelted such mixtures yielded the bronzes which were the characteristic metals of this early period. As the supply of tin ore gave out, the early smiths looked for further supplies and thus spread the art of metallurgy to central Europe and beyond to the coasts of the Atlantic.

Mining for ores now became an important craft, and the techniques used by prehistoric man for the production of flint and other useful stones were elaborated and perfected in the mines of the Sinai peninsula, the Armenian mountains, Asia Minor, the Balkans, and central Europe. Gold, silver, and copper and its alloys (and in some cases meteoric iron) came into general use, but bronze was still too costly to displace all stone tools and implements, and in many cases stone tools were still more efficient than the early metal products.

The simple pottery techniques of the Stone Age also underwent great changes with the introduction, about 4000 B.C. of the potter's wheel, which enabled man to create more elaborate and new types of pottery. Such was the flourishing of the potter's art that pottery became one of the most important means of distinguishing local cultures from one another. The art of glazing pottery was discovered and pottery could thus be decorated and rendered impervious. The glaze could be prepared in crucibles and cast into small strips which, when hot, could be moulded round a sand core, which was removed after cooling. Thus small glass objects were fashioned; perfume bottles, ointment containers,

and beads were produced during the many centuries before glass blowing was invented about 50 B.C.

The wheel was first turned to use for carts and carriages about 3000 B.C. (or perhaps even somewhat later) when sledges were fitted out with them. However, wheeled carts played only a small part in traffic, as there was no long-distance travel except for luxury goods, and pack animals were more in favour. The transport of heavy material such as timber followed the shortest track to river or coast and vessels made from basketry, or bundles of reeds, or of timbered construction evolved from the dugout canoe, were preferred. Carts played a certain part in the army for the transport of heavily armed warriors to the battlefield, but not until the advent of the horse in the Near East and its use to move the light war-chariots of the second millennium B.C. did they change the aspect of battles and play the part of the 'tanks of antiquity'.

The greatest changes took place in agriculture and the techniques connected with it. From the primitive hoe or digging stick which barely scratched the soil and gave poor harvests, Bronze Age man had turned to the plough, drawn by oxen or men, which was supplemented in the river valleys by irrigation and yielding harvests sufficient to sustain larger populations and which could be bartered with the mountain-dwellers for their ores, precious stones, and timber. Irrigation on a large scale as practised in Egypt and Mesopotamia required the joint effort of many to build and maintain the dykes and canals; it promoted cooperation between neighbouring settlements and stimulated the formation of larger political units, which were basically 'hydraulic provinces'. Observation of the rise and fall of rivers stimulated the introduction of an 'inundation calendar' and the watching of the heliacal rising of stars and other celestial phenomena. Registration and measuring of plots and fields were needed to re-establish the boundaries after the flood, to tax the farming population, and to supply the cities in kind. The building of dams and canals meant moving large quantities of earth, which had to be calculated to pay labour. Building technique profited from the experience thus gained. Again, the land inundated by the natural overflow of the river was supplemented with fields artificially

inundated by raising water with leather bags, pails, or swapes and later, in Hellenistic days, with more elaborate machinery moved by men or beasts.

Bronze Age agriculture turned from the more primitive cereals like emmer to the better types like wheat and barley; it widened the range of vegetables and fruit cultivated in the gardens and orchards. Oil-bearing plants such as olive trees were now widely grown. Bees were kept not only to produce the only form of sugar available to the ancients (apart from some date-syrup) but also to yield wax, which was an important medium for wax-painting. Pre-roasted grain was turned into flour in grain-rubbers until the second millennium B.C., when rotary motion was applied to the millstones and simple forms of querns arose, though grain-rubbers were still in use in ancient Greece. The art of fermentation was understood, and barley (sometimes mixed with emmer) was turned into beer, which was widely drunk in Mesopotamia and Egypt. The latter country was also famous for the wines it produced, and in both countries the art of making vinegar was common knowledge. Meat was eaten by the rich only – it was preserved by smoking and drying – but fish was a more common food and was transported far inland as the art of pickling was well understood. This art had even stimulated the mummification of human and animal bodies in ancient Egypt, where religion demanded the preservation of such bodies.

In general it can be said that the techniques evolved in the kitchen were of great importance to chemical technology, and many terms in ancient technology remind us of the fact that the original operation or apparatus hailed from the kitchen.

In building too this period brought new techniques. It saw the rise of the use of sundried and burnt bricks, especially in Mesopotamia, where the natural seepages of bitumen were turned to use to produce an excellent mortar for brick walls and floors. In Egypt, where mining techniques were better known, slabs of natural stone were quarried and applied in brick buildings, until Imhotep, vizier of King Zoser (2750 B.C.), attempted to build entirely with brick-shaped stone blocks, which were fashioned on the spot after being stacked without mortar. Later he

learned to cut the stone directly into shapes more suitable for building and thus created architecture in natural stone, which a few generations later culminated in the well-known pyramids of Gizeh. In Mesopotamia the first vaults were developed and the Assyrian engineers learned to bridge rivers. City streets were often paved, and the art of building a proper sewer system was thoroughly understood all over the Near East and the Indus valley.

In these few lines we can hardly do justice to the great variety and ingenuity of the ancient craftsmen, who worked unaided by the scientists of their day but nevertheless laid the foundations of modern technology. We must now, however, turn to the birth of Greek science, which was to absorb the older achievements of the Near East and transmit them to our generation.

CHAPTER 2

Greek Science, an Aspect of Greek Philosophy

THALES OF MILETUS

IT has become a tradition to begin the history of Greek natural science with Thales of Miletus (*c.* 640–546 B.C.) since, according to the doxographers, he asserted that the *archè* (the prime element) of all things was water.

It is perfectly understandable if a modern reader regards this as only a feeble claim to such an exalted historical position. He will naturally want to inquire into the exact content of the thesis and the grounds on which it is based, but he will not get a satisfactory answer to either question.

Thales probably meant that all material things originate from water, consist of water, and turn into water when they perish, so that the permanent feature behind the changing phenomena is water; but this vague assertion is not formulated in the exact terms which would have been so desirable, and any statement of grounds for it are lacking. Numerous attempts have been made to fill these gaps, but the result is no more than plausible guess-work and is not likely ever to be anything more with the absence of any documentary evidence. Are we nevertheless to regard this as the origin of modern science, that great creation of the human mind?

There are three reasons (one negative and two positive) for answering this question in the affirmative:

(i) There is no trace in Thales's thesis of the mythological element which played such an important role in earlier attempts to explain nature. There is no question of gods, demons, or nymphs who bring about natural events and whose action does away with any requirement for a casual explanation.

(ii) Leaving open the question what experience was the basis of

Thales's thesis (was it the fact that water may occur in a number of widely different forms or its indispensability to the life of animals and plants?), we may note that he used his hypothesis to explain other phenomena. Thus he answers the old question as to what supports the earth by saying that it floats like a flat disc on the water of the ocean.

(iii) Our modern science has descended in a continuous, uninterrupted line from the thoughts of Thales and men of the same stamp among his contemporaries. We are as fully justified in beginning the history of science with him as we are in beginning a person's biography from the time he was an infant.

THE GREEK PHYSIOLOGISTS

In the last section we mentioned Thales' contemporaries. The history of Greek philosophy classifies them with him as the Ionic natural philosophers, while in ancient times they were also called the Ionian physiologists, which means the same. It lists as such:

Anaximander (610/9–546/5 B.C.), who postulated as the origin of things the apeiron, the indeterminate which is capable of being further determined.

Anaximenes (585–528 B.C.), for whom everything originated from air through condensation and rarefaction.

Heraclitus (540–*c.* 475 B.C.), who would not consider anything that remains the same with changing phenomena as the essence of what nature presents to us, but accepted only inconstancy itself, and consequently, with that youthful intrepidity which was always a characteristic of Greek thought, sought the true nature of things in what we experience as being the most inconstant of all: fire.

The modern reader, remembering his science lessons, will be up in arms again. Is it the history of science that you are about to relate to us, he will ask, or the history of philosophy? The thinking of the Ionian physiologists may be on a higher plane than the mythological or theological level, which according to Auguste Comte (1798–1857) was the first stage in the development of thought, but it is apparently still at the metaphysical stage, which he regarded as the second.

The answer is obvious. There is no history of science yet, for the simple reason that there was not yet anything like an independent science side by side with philosophy. The latter, however, dealt with problems which we would now consider to be purely scientific and hence we can not neglect them in a history of science.

In the course of the development of Greek thought some of these problems detached themselves more or less from philosophy. We shall deal with this in the next chapter. For the present we are concerned only with various philosophical trends which are of importance to the development of science. We shall deal with them from this point of view only. Our discussion has therefore not the slightest pretension to providing an introduction to Greek philosophy.

TRENDS IN GREEK PHILOSPHY

Seven of these trends will be discussed:

(*i*) *Pythagoreanism*

For our purpose the most important (but also the most typical in the absolute sense) characteristic of this doctrine, which derives its name from the somewhat legendary philosopher, Pythagoras of Samos (*c.* 570–497/6 B.C.), is its great interest in, and great appreciation of, number as a metaphysical principle. Tradition ascribes to Pythagoras the discovery of the fact that small number ratios (namely 2 : 1, 3 : 2, 4 : 3) correspond to the most consonant musical intervals: octave, fifth, and fourth respectively, the greatest of the two terms of such a ratio sometimes being ascribed to the lowest tone of the interval (in this case evidently a ratio of lengths of string or pipe is envisaged) and sometimes to the highest (which calls to mind something like vibration frequencies). Whether this discovery inspired the Pythagoreans to more intensive speculations on number or only strengthened a tendency which was already present, it is a fact that everywhere they began to see numbers and numerical ratios.

This 'everywhere' is to be taken absolutely literally. In astronomy numerical ratios were supposed to exist between the distances of the various heavenly bodies from the centre of the

world, and since these ratios also meant musical intervals, these intervals came to be regarded as being present in the celestial spheres. From this sprang the wildly speculative doctrine of the harmony of the spheres which for ages was again and again to fascinate people of a mystical turn of mind.

Unfortunately, this fascination was occasionally founded on a misunderstanding: harmony was understood to be the effect of the sounding together of two or more tones, whereas according to the Greek conception, it was an interval of two successive tones.

But numbers are indeed hidden everywhere: in geometrical shapes (1: the point, 2: the straight line, 3: the plane surface, 4: space); in moral qualities (4: justice, 7: favourable opportunity); in social institutions (3: marriage).

Aristotle (384–322 B.C.) gave two succinct formulations of this Pythagorean way of thinking: things are numbers; the entire firmament is harmony and number.

In its subsequent development Pythagoreanism led on the one hand to unbridled and sterile speculation on numbers, on the other hand to an extremely fruitful endeavour to discover everywhere in nature laws capable of being mathematically formulated; finally, when this endeavour had been repeatedly successful, to the realization that science should use mathematics as the language in which to express its thoughts.

In the field of astronomy Pythagoreanism has a special significance for two reasons:

(*a*) In all probability this school created the idea that the motion of the sun in the sky can be accounted for by regarding it as the result of two compounded motions: an annual motion with respect to the fixed stars along a great circle of the celestial globe, called the circle through the centres of the zodiacal constellations (later: oblique circle and finally: ecliptic), and the daily rotation together with the fixed stars round the axis of the celestial globe.

(*b*) Here too, in defiance of the seemingly unimpeachable evidence of the senses, the idea originated that the earth might possibly not be the central motionless body of the universe. This conception was elaborated into a cosmic system ascribed to Philolaus (middle of the fifth century B.C.) in which the earth is

assumed to turn round a central fire as one of a group of ten heavenly bodies (the nine others being counter-earth, the moon, the sun, the five planets, and the sphere of the fixed stars).

It is a waste of time to try to distinguish one man from another among the Pythagoreans, to try to fix them in place and time and to ascertain their individual contributions. What links the Pythagoreans is a mode of thought rather than a school or sect. This system may crop up at various places and times, as for example in the so-called Neo-Pythagoreanism about the beginning of the Christian era.

(*ii*) *Eleaticism*

This was a philosophical trend that took its name from the city of Elea in lower Italy, where Parmenides (*c.* 500 B.C.), the founder of the school, was born. Its most characteristic feature is vehement denial of the reality of any change. Change is declared to be unreal semblance and – with a consistency typical of Greek thought – therefore excluded from the sphere of scientific interest.

The Eleatics recognized only an immutable 'Being' which was uniformly coherent and indissoluble. Parmenides compared it to an homogeneous solid sphere. An important consequence was the impossibility of the void; this would be a non-being and therefore did not exist. For the particular case of motion the Eleatic tenet was defended by means of subtle paradoxes by Zeno of Elea (*c.* 490 – *c.* 430 B.C.), who was thus the first to demonstrate the difficulties of conceiving a continuum.

(*iii*) *Atomism*

The philosophy bearing this name, inaugurated by Leucippus (sixth century B.C.) and Democritus (*c.* 460–*c.*370 B.C.), may be regarded as a reaction to Eleaticism with the object of rescuing the reality of change. Instead of the solid sphere of the Eleatics an infinite multitude of particles immutable in themselves, the atoms, was assumed. To provide the possibility of motion it was argued that the non-being of the Eleatics also exists; this is the void in which the atoms can change their positions.

As a result of differences in shape, size, position, order, and state of motion the atoms bring about the situations and events which together constitute nature. The atoms themselves are internally immutable and have no properties except impermeability.

Since the human soul (the life principle) also consists of atoms (a particular type, small, round, and smooth) and all contents of consciousness (perceptions) are only a subjective semblance (and thus unimportant), atomism leads to an absolutely atheistic, materialistic conception of life and the universe. It was to this conception that it mainly owed its initial survival. The philosopher Epicurus (341–270 B.C.) used it as the scientific basis of his anti-religious system of thought, and the Roman poet Titus Lucretius Carus (95–55 B.C.), who admired Epicurus, cast it into a classic mould which was to remain preserved throughout the ages in his famous didactic poem *De rerum natura* dedicated to the defence of Epicureanism.

(*iv*) *Platonism*

In this philosophy of the Athenian philosopher Plato (429–347 B.C.) complete reality is accorded only to a supersensible world of forms or ideas of which the things of the world capable of sense perception are but vague reflections or crude imitations. Between these two worlds mathematics occupied an intermediate position difficult to describe. Mathematical reasoning had no relation to empirical objects, not even to drawn figures, but to ideal spatial forms and numbers. Instruction in mathematics therefore constituted the true preparation for initiation into philosophy.

Correspondingly, true astronomy did not deal with the perceptible motions of the visible heavenly bodies, but with the ideal motions of mathematical points in an imaginary sky which was substituted for that of sense perception. These points cannot describe other than uniform circles. The task of the astronomer was to interpret the irregularities noted in the celestial motions (the non-uniformity of the motions of sun and moon; the loops in the planetary orbits) as the result of compounding various uniform circular motions. The technical term for this is: saving the

phenomena (*δωζειν τὰ φαινόμενα*). The astronomers' task to proceed in this manner is termed the Platonic prescription or problem.

Owing to its inherent extremely low evaluation of empiricism Platonism had on the one hand a tendency which could not be conducive to the flourishing of science. On the other hand, it has provided an essential feature of science for all time by distinguishing between essentially inexact experience acquired through the senses and the ideal picture which scientific thought substitutes for it. In its efforts towards mathematical treatment Platonism shows a close relationship to Pythagoreanism. We shall therefore frequently speak of Pythagorean Platonism.

(*v*) *Aristotelianism*

Whereas Plato had recognized only ideal motion as real in contrast with the Eleatic denial of the reality of all change, Aristotle demanded recognition of the reality of all processes in the empirical world. He took as his basis a distinction between actual and potential being and the dual concepts of form and matter connected with it. Both are too closely related with his entire metaphysical system to be dealt with here in detail. Confining ourselves again to the physical aspects, we find as characteristic properties:

(*a*) The doctrine of the composition of all earthly substances of four basic substances or elements termed earth, water, air, and fire. These are not to be understood as the empirical substances so termed, but as ideal, only imagined, components. Each of them represents a combination of two out of four basic properties: dry and cold, moist and cold, moist and warm, dry and warm. The elements may change into one another through a basic property turning into its opposite. Thus water is transformed into earth when a liquid is frozen and into air when a liquid evaporates. The manner in which elements are present together in a compound substance, although designated by the word *mixtio*, comes within the concept of chemical combination. The description of *mixtio* as the fusing into one of the changed, uniting components was to give rise to commentators in Antiquity and the Middle Ages to

the much discussed question as to whether the elements continue to exist in the compound, and if so how. They were also to be concerned with the problem as to whether or not material bodies are infinitely divisible while yet retaining their specific properties. The conception that there is a lower limit to division was already recognized, if not yet by Aristotle himself, certainly by his ancient and medieval commentators in their theory of the *minima naturalia*. These *minima* should be properly distinguished from the Democritean atoms; unlike them they are not unchangeable and they possess properties – those of the macro-substances constituted by them.

(*b*) The differentiation between the motions of earthly bodies into natural and forced, the first category resulting from the nature of the substance of which these bodies consist (in accordance with the principle *operari sequitur esse:* behaviour results from being), while the second can only be temporarily imposed from without.

There are bodies which by their nature fall down (i.e. move towards the centre of the world); these are called heavy. In contrast with them there are light bodies which by nature rise (i.e. move towards the sphere of the moon). The natural motion of a body may depend on the medium in which it happens to be: wood is heavy in air, but light in water.

(*c*) The contrast between earth and heaven. In contrast with the natural motions of falling and rising of earthly bodies, which are never anything but temporary, there is the eternal uniform circular motion of the celestial bodies. In view of the principle *operari sequitur esse* they therefore do not consist of the four earthly elements, but of a fifth element (the *quinta essentia* or ether), to which the uniform circular motion belongs by nature and which unlike the four others is internally immutable. This leads to two consequences: (1) The structure of the world is essentially geocentric: the heavy earth can by its very nature do no other than rest in the centre of the world. If at any time it had not been there, it would have reached this position long ago in natural finite motion. (2) It is logically impossible to apply concepts and reasoning of earthly science to the heavenly bodies; in

particular, it is an absurd thought that the earth itself should also be a heavenly body.

(*d*) The impossibility of a void space (vacuum). Various arguments are advanced for this, which are partly connected with the theory of the natural motions of falling and rising and partly with the theory of place. We shall not enter into this, and only mention that a void is felt as a logical contradiction: it would be a *locus sine corpore locato*, a place in which nothing is placed.

(*e*) The acceptance of the axiom: 'every moving body is moved by something external which is in contact with it' as the foundation of the theory of the motion of lifeless earthly bodies, in consequence of which: (1) A body which is removed from all external influences is in a state of rest. This can be called the ancient law of inertia. (2) In the case of every forced motion the question as to the *motor conjunctus*, the cause of motion connected with the body, must be asked. In a rather complicated theory the surrounding air is referred to as such in the special case of a heavy body being thrown upwards or sideways. This constitutes another argument against the void: no throwing movement would be possible in it.

(*f*) The so-called fundamental law of peripatetic* dynamics, which is connected with the above and implies that the velocity of a body propelled by an external cause (force) is proportional to the propelling force F and inversely proportional to the resistance R which opposes the motion; this resistance seems to comprise inertia as well as friction and air resistance. Fully aware of the anachronism of which we are guilty, we express this law for the sake of convenience by means of the formula:

$$V = C\frac{F}{R}$$

an essential condition being that $F > R$, otherwise no motion results. Written in the form:

$$F = C_1 R V$$

* Aristotelian philosophy is also called peripatetic because Aristotle gave his instructions while walking in the Lyceum (περιπατεῖν to walk).

it constitutes the ancient analogue to the fundamental law of Newtonian mechanics:

$$F = m\,a$$

The pronouncements on falling and rising movements can be summarized with the same proviso as above in the formula:

$$V = C\,\frac{G}{R}$$

where G represents the weight (or lightness as the case may be) of the body and R the resistance of the medium. It must be stressed that these formulations in words and symbols, which have been adapted to our habits of thought, specify and accentuate the Greek ideas in a manner which cannot truly be permitted. For this reason not every conclusion drawn from these formulae can be passed off as an assertion of Aristotle's.

We have dealt with the scientific aspects of the Aristotelian system in greater detail than any other because no other Greek philosophy has exercised such a prolonged and powerful influence on the practice of science. In the Middle Ages there were practically no limits to its influence on European thought. Its effect on astronomy and physics can be felt right into the seventeenth century and on chemistry until well into the eighteenth. This consideration justifies the great attention historians of science have always paid to Aristotelian thought.

The question of its intrinsic value takes second place. The modern scientist is inclined to regard this value as very small. He finds numerous assertions which he rejects as incorrect or even silly; he continually notices the habit of advancing premature theories on the basis of some superficial observations and drawing inferences of universal import from insufficient evidence.

However objectively right this criticism may be, it is lacking in depth. We must not lose sight of the fact that of all Greek thinkers Aristotle has the most outspoken empirical attitude towards nature, which was to prove indispensable for the creation of science. Nor should it be forgotten that science is also empirical in that the manner in which it should be practised can only gradually be learned by experience. It remains the great merit of Aristotle (and of Greek thinkers in general) that he made

nature the object of scientific investigation. This is much more important than the fact that he frequently took paths which in later ages were seen to have led him astray. The history of science convincingly shows that any theory is better than no theory. In the long run, any mistakes that are made enforce their own correction by their incompatibility with experience. But if no attempt is made to understand nature, there can be no progress.

(*vi*) *Stoicism*

As Stoic philosophy is predominantly ethical in nature, its scientific implications are fewer and less important than those of the systems dealt with so far. Its (refined) materialism, however, involves interest in and appreciation of scientific questions, while the fundamental conviction that the world is an ordered cosmos governed by a principle of reasonableness and lawfulness likewise created a favourable environment for science.

(*vii*) *Neo-Platonism*

This is a late form of Greek philosophy (third century of the Christian Era) which, as its name indicates, envisages a revival of Plato's teachings; it also aims at a synthesis of this doctrine and Aristotle's, thus contributing to the maintaining and propagating of the strong influence that both these doctrines had in the ages to come.

A characteristic trait of Neo-Platonism is its metaphysically based contempt for all things material, from which indifference regarding natural processes results. The anti-empirical attitude already inherent in Platonism was therefore further accentuated, so that the new philosophical movement could not be expected to be conducive to the flourishing of science.

The above brief summary of Greek philosophy in its scientific aspects will be sufficient to convince the reader that it was an important factor in the history of science. Its effect may have been propitious or the reverse, but at all events it was always intimately involved in the early stages of science. Greek thinkers made a start with the practice of science; they introduced into it a number of modes of thought, concepts, terms, and methods which were

never to disappear and the influence of which percolates through to present-day science.

We conclude this chapter with a summary of the most relevant points in which the Greeks helped to determine the future development of science.

In *Pythagorean Platonism* we find the origin of the realization of the essential importance of mathematics to science. The view that the proper task of science consists in creating a mathematical system the deductions of which are in agreement with observation and giving rise to prognostications that can be subjected to empirical vertification is ultimately derived from the Greek concept of the rescuing of phenomena.

In *Eleaticism*, with its conviction of the immutability of true being, we have the source of all endeavour to discover the invariables in natural phenomena (which were later to lead to the formulation of the principles of conservation) and in theories which attempt to reduce causal dependence to identity.

In *Democritean Atomism* we find the idea, essential to science, of the corpuscular structure of what appears to superficial perception to be a continuum, and also the root of all kinetic theories of matter. Its internal connexion with Eleaticism is reflected by the support it gives to the formulation of principles of conservation. In particular, it is the earliest source of the energy principle.

In *Aristotelianism* we find the recognition of empirical data as the proper objects of scientific investigation and, as a result, a fundamentally empirical attitude towards nature. Attempts to discover general laws, particularly concerning motion, find their origin here, also the idea of the reduction of the multiplicity of substances observed to combinations of a limited number of basic substances.

In *Stoicism* we find the origin of the conception of the whole of nature as a great coherent entity which is subject to an all-embracing system of rationally comprehensible laws.

Having outlined the sources of stimulation for science in Greek thought, we shall concern ourselves in the next chapter with the separate sectors of Greek science.

CHAPTER 3

Greek Science

MATHEMATICS

IN this chapter we give a brief review of those aspects of natural science which in Greek antiquity were no longer regarded as part of philosophy, but which led a more or less independent existence. It seems useful to speak first of all about the history of mathematics. Although this is no longer looked upon as a branch of natural science it is, as was seen in Chapter 1, closely related to it, and it was of fundamental importance for the development of natural science.

An intriguing problem in the history of mathematics is the extent to which Greek mathematicians may have borrowed their knowledge from the Babylonian and Egyptian cultures, but it is not necessary to go deeply into this question in our present context. It is at all events an undisputed fact that the Greek method of treating mathematics, i.e. as an abstract logical edifice on the basis of definitions and axioms, constitutes a completely original contribution of the Greek mind to the development of mathematics. Under the influence of Platonism the link with empirical reality, from the needs of which it had formerly sprung, was severed completely. If mathematics had already acquired great significance for natural science in Antiquity, this is due not so much to any direct practical applications as to the attempt to cultivate natural science as if it were a branch of mathematics. For some subjects such attempts were in fact successful.

For the purposes of this work it will suffice to mention a few great Greek mathematicians. After a long period of development Euclid of Alexandria gave definitive form to the systematic exposition of mathematics about 300 B.C., and this form has been accepted as a model for its treatment throughout the centuries. In

the third century B.C. Archimedes of Syracuse (*c.* 287–212 B.C.) developed rigorous methods for determining areas and volumes, providing the first stage of the development of what in the seventeenth century was to expand to integral calculus. We shall presently return to the manner in which he treated physical subjects from a mathematical viewpoint. A short time later Apollonius of Perga (*c.* 262–*c.* 170 B.C.) raised the theory of conic sections to a level which had to wait until the seventeenth century to be surpassed. He was also responsible for certain mathematical expedients in the field of astronomy, the requirements of which subsequently gave rise to the *Sphaerica*, i.e. spherical geometry and spherical trigonometry. The many other fruits borne by the mathematical genius of the Greeks have no direct bearing on the evolution of natural science and are therefore disregarded here.

The consideration of Greek natural science which now follows is divided into subjects arranged according to the scientific significance of the results obtained. In view of the short treatment prescribed it will not always be possible to adhere to the chronological order of the various theories. The history of Greek science extends over approximately ten centuries and statements that 'the Greeks' discovered this and thought that are therefore inadmissibly vague. However, as the past always appears to us in an abridged perspective, expressing oneself in this way from time to time is unavoidable.

ASTRONOMY

We have already seen (p. 37) how Plato directed the path of development of mathematical astronomy by his demand to save celestial motions by means of systems of uniform circular motions. An attempt to meet this demand was undertaken by the great mathematician Eudoxus of Cnidus (*c.* 408–355 B.C.) in his theory of concentric spheres, which assumed for sun, moon, and each of the five planets a set of revolving spheres fitting into one another, each sphere of a set entraining those inside it.

The celestial body was situated on the equator of the innermost

sphere. The axes of rotation and circling times had to be so selected that the resultant motion of the body corresponded to what could be actually observed. Eudoxus required a total of twenty-seven spheres: one for the fixed stars, four for each of the five planets, three for the sun, and three for the moon.

Each of the planets describes a figure 8 curve on the surface of the second sphere of its set. The motion round this curve combined with that in the zodiac accounts for the retrogradations and stations observed in the planet's course.

This theory strikingly illustrates the view of mathematical astronomy which was held by the Greeks. There is no reference to any mechanism to set the actual bodies in motion, nor may it be asked what the spheres are made of, how they are fitted together physically, and whence their motive power is derived. They are mathematical spheres and the innermost of each set does not in fact bear the sun, the moon, or a planet but a mathematical point representing a celestial body. The entire system is a kinematic representation of the actual motions of the celestial bodies. For a true Platonist it constituted an ideal reality, of which the firmament perceived through the senses was an imperfect copy.

The Greek astronomers were, however, in spite of the Platonic trend of their thought, sufficiently scientifically minded to recognize experience as a criterion in assessing the value of a mathematical representation; the mathematical conclusions had in the end to conform to what observation revealed.

It was found that this was not the case with the system of Eudoxus. As all spheres had the Earth as their centre, the distances from all celestial bodies to the observer on Earth ought to be constant, but it was known for at least some of them that their apparent diameters were variable. This was sufficient reason to reject the system.

We cannot deal here with some attractive modern reconstructions of the quantitative aspects of Eudoxus's system or with the extension given to it by Callippus (born 370 B.C.) and Aristotle.

A completely different method of 'saving' the phenomena was presented by the astronomer Hipparchus (second century B.C.) who appears to have built upon the discoveries of Apollonius.

His theories were further elaborated and refined by the Alexandrian astronomer Claudius Ptolemy (second century A.D.) who embodied them in the great handbook of Greek mathematical astronomy which has survived in history under the name *Almagest* (a corruption of the Arabic translation of the Greek title *Megale Syntaxis: The Great Composition*). This work controlled astronomic thought virtually unchecked until the sixteenth century; it forms one of the most striking examples of the immense influence which Greek culture has exercised on world history.

No attempt will be made to discriminate between what in the *Almagest* is the spiritual property of Hipparchus and what is the personal contribution of Ptolemy. The wide range of the work and the complexity of its content also prevent us from dealing with it in detail. We shall confine ourselves to a brief summary of the contents and a short description of some of the methods used.

Although Ptolemy is enough of a Platonist to consider it the task of astronomy to invent mathematical systems of motion without any obligation to explain how these might be realized physically, he repudiates in his introductory remarks, on grounds which are derived from Aristotelean physics, the idea that the Earth could be considered as in motion in order to 'save' the phenomena. He admits that the daily revolution of the sky may be mathematically understood as the reflection of a daily rotation of the Earth on its own axis, but contends that this is physically absurd. His principal argument, which was to be repeated through the centuries, was that if the earth were rotating in a west to east direction (this would have to be assumed to account for the daily motion of the sky from east to west) we ought to see everything that is not firmly connected to it (such as clouds or birds) moving quickly westwards. The problem was later defined concretely as follows: a stone thrown up vertically ought to drop west from the throw-up point. We see here the influence of what we have termed (see p. 39) the ancient principle of inertia: as soon as the link between a body and the earth is broken, the motion it had received from the moving earth is also cancelled; it stays behind.

In later chapters of the first book of the *Almagest* Ptolemy deals with the principles of Greek goniometry and trigonometry

which are constantly applied throughout the work. These differ from present-day practice in that an arc $AB = \phi$ of a circle (Fig. 1) is determined by its chord AB and not by its sine BC (i.e. half

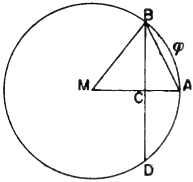


Fig. 1. The relation between the Greek chord-function and our present day sinus-function.

of the chord BD of double the arc). This appears to be simpler, but proves upon closer analysis to be less practical. All calculations according to the Greek method may, it should be said, be immediately converted into the form with which we are familiar by the ratio

$$\text{crd}\ \phi = 2 \sin \frac{\phi}{2}$$

in which crd ϕ represents the chord subtending the arc. The table of chords which Ptolemy gave and the calculation of which he explained, may therefore also serve as sine table. After thus providing himself with the necessary mathematical apparatus he dealt in the remainder of Book I, and in Book II, with everything that he will ever require from the field of spherical astronomy.

Book III is devoted to the motion of the sun. Here we meet a concept that well typifies Greek astronomy and which was to become of great significance historically: the concept of eccentric circular motion. This was used to explain the fact already known in the fifth century B.C. that the seasons are not of equal length. This seems to indicate that the sun does not pass through the ecliptic uniformly, which is, however, ruled out by Plato's axiom. This axiom can be maintained by assuming that the sun does in fact move through the ecliptic uniformly but that the observer on earth is not in the centre C of that circle but at an eccentric point E (Fig. 2). Instead of speaking of an eccentric observer, however, the circular motion is said to be eccentric and the circle is called an eccentric.

This idea was developed by determining the eccentricity $CE = e$

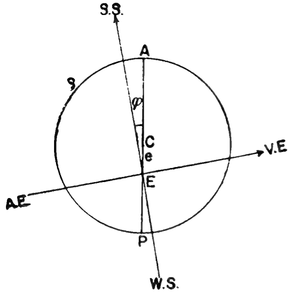


Fig. 2. Eccentric Motion. The Sun S rotates uniformly on the circle centred at C, but its motion seems to be non-uniform to an observer at E. VE = vernal equinox; SS = summer solstice; AE = autumnal equinox; WS = winter solstice; A = apogee; P = perigee; AP = line of apsides; $CE = e$ = eccentricity.

(the radius of the circle is put at 1) and the angle ϕ, which determines the position of the line of apsides AP in respect of the annual points. Ptolemy found $e = 1/24$ and $\phi = 24° 30'$. (The Greek mode of expression for this is that the apogee lies at π 5° 30′, π denoting the sign *Gemini* (the Twins) of the zodiac.)

Ptolemy then showed that the phenomena may also be explained in another way. In this case it is imagined (Fig. 3) that the

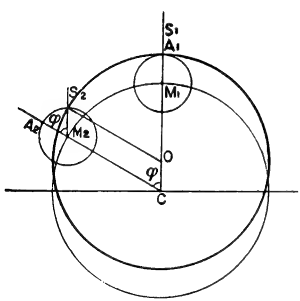


Fig. 3. Special epicyclic motion. The Sun describes a circle centred at M, which rotates on a circle centred at C. The movements are both uniform and have equal angular velocities, but in opposite directions. This special epicyclic motion is equivalent to an eccentric motion around O ($CO = MA$).

observer stands at C. The sun does not describe the circle centred at C, but another smaller circle (called the epicycle), the centre M of which moves round the first circle (called deferent). The sun S is imagined initially at a point A of the epicycle which is then at A_1. M is now in M_1. After a time M has come to M_2 and A therefore to A_2 (the epicycle must be imagined as fixed to the edge of

the deferent). Let $M_1 CM_2 = \phi$. It is then assumed that the sun has also passed through an arc ϕ on the epicycle but in the opposite direction; it is now at S_2. It can now easily be shown that the sun has in fact passed through a circle with centre O ($CO = MA$), within which the observer stands in an eccentric position at C. The two hypotheses are therefore equivalent.

It is characteristic that there is no attempt whatsoever to find out what the sun does in reality. It is again quite obviously a question of a kinematic description, not of a physical mechanism.

The complete course of the sun's orbit can now be mathematically described according to either of the two hypotheses. This is not done by means of formulae as we are accustomed to, but in tables from which the observed position of the sun can be read off for any given time. By comparing this calculated position with that actually observed, the accuracy of the theory can be empirically verified.

The above example of an epicyclic motion constitutes a very special case: the angular velocity of the motion on the epicycle was equal to that of the motion of the centre of the epicycle on the deferent and the directions of motion were opposed. If these special hypotheses are dropped, if the epicyclic motion is combined with an eccentric motion and if the centre of the deferent is also admitted as turning round the position of the observer, numerous other possibilities arise, which are used in the following books to explain the motions of the moon and the planets. This is done in Books IV and V for the moon, and in Books IX–XIII for the five planets. We shall not enter into this here, and shall merely show how it is possible in principle to explain the occurrence of retrograde motions by means of an epicycle.

When the planet P (Fig. 4) is at point C_1 of the epicycle centred on M, and the directions of motion are as indicated in the diagram, the observer at E will see it move in a contrary direction to that point M, while for the largest part of the course (certainly when the planet is at C_2) the directions in which E sees M and P move, coincide. Around C_1, therefore, the planet is retrograde.

In spite of the high complexity of his various systems of motion, Ptolemy did not fully succeed in accounting for observed

phenomena. This led him to introduce another new refinement of the picture which was also to prove of great historical significance. It is now assumed (Fig. 5) that the centre M of the epicycle

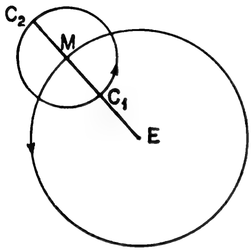


Fig. 4. General epicyclic motion, explaining retrogradations.

moves over the deferent in such a way that it is not the radius vector CM which turns uniformly with respect to CA, but the radius vector PM from a point P lying on the line of apsides on the other side of C from the observer E. Point P will later be called *punctum aequans* (equant, i.e. equalizing point). It is clear that Plato's axiom is in fact violated by the introduction of this new assumption. It may of course be formally maintained by regarding another circle with P as centre (the *circulus aequans*), over which the point of intersection B does run uniformly with

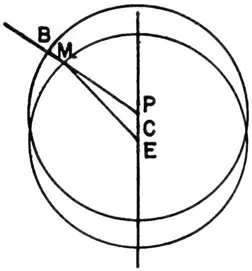


Fig. 5. Epicyclic motion with equant. The *radius vector PM* rotates uniformly around the *punctum aequans P.*

the radius vector PM, but this is rescuing the axiom rather than saving the celestial phenomena.

We conclude our brief discussion of the *Almagest* by noting that Book VI deals with the solar and lunar eclipses, and that Books VII and VIII contain a catalogue of 1022 stars, for each

of which the latitude and longitude are given in addition to its magnitude. Reference is also made to the phenomenon of precession, which had been discovered by Hipparchus. By comparing the positions of stars in his own day with former observations made by Aristyllus and Timocharis (third century B.C.), he had found that the longitudes of a number of stars had increased by an equal amount, from which he concluded that there was a slow motion of the entire sky of fixed stars. Later the same phenomenon was construed as a retrogressive movement of the vernal equinox, for which the term precession was retained. Ptolemy estimates the annual amount of precession at 36″, which comes to 1° per century. The true value is around 50″ a year.

Attention is also devoted to a question which was of importance to Greek astronomy, that of the rising and setting of fixed stars. This must not be understood as meaning the daily appearance above and disappearance below the horizon, but a star's becoming visible or invisible in the twilight. We are touching here upon the oldest section of astronomy; already in pre-scientific ages certain dates of the year which were important for agriculture had been indicated by the rising and setting phenomena of well-known fixed stars.

After this brief summary of the contents of the *Almagest* we shall now give an extremely schematic representation of the Ptolemaic system, from which all details (which really constitute its greatest achievement) have been omitted (Fig. 6). It is assumed that the observer is not standing eccentrically, that there are no equants, etc. A peculiarity of the system is now revealed all the more clearly – that the motions of all the planets are related to that of the sun. For the inner planets the centres of the epicycles lie on the Earth–Sun line; for the outer planets the radius vector from the centre of the epicycle to the planet is parallel to this line. This might have been an indication that the sun is more than a body rotating round the earth among six other bodies. The observation was in fact made, but without any astronomical conclusions being drawn from it.

The short sketch of the world-picture of the *Almagest* given above needs to be amplified in three remarks:

(i) As in the Ptolemaic system the earth is not the centre of the celestial movements but is resting; we therefore prefer the term 'geostatic' to the customary 'geocentric'.

(ii) Not all Greek astronomic systems are geostatic.

(iii) In addition to mathematical astronomy, which aims exclusively at describing the celestial phenomena kinematically, there is also a physical astronomy which seeks to explain what is actually seen to be taking place in the sky.

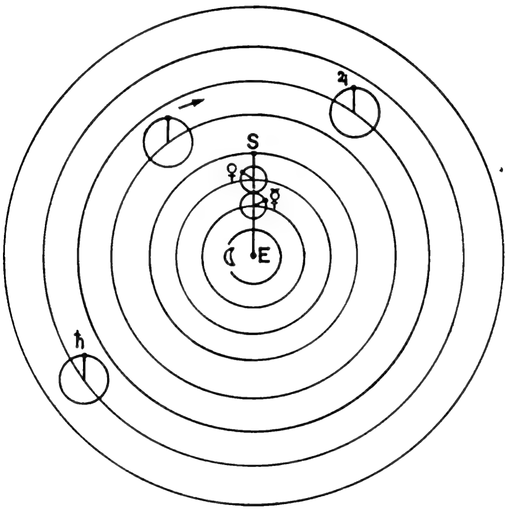


Fig. 6. Schematic picture of the Ptolemaic System. E = Earth, ☿ = Mercury, ♀ = Venus, S = Sun, ♂ = Mars, ♃ = Jupiter, ♄ = Saturn, ☾ = Moon.

With regard to (ii) we shall confine ourselves to noting that, according to the testimony of Archimedes (287–212 B.C.), the astronomer Aristarchus of Samos (*c.* 320–*c.* 250 B.C.) conceived a heliostatic world-picture, in which the earth was a planet like the others, revolving round the sun in a year and rotating round its own axis in a day. Aristarchus is thus correctly styled the Copernicus of Antiquity.

His appearance had no perceptible influence on the later de-

velopment of Greek astronomy. There is no proof that he developed his system in sufficient detail to enable calculations to be made of tables for the motions of sun, moon, and planets, which constituted the main purpose of astronomical theory. And the concept of a motion of the earth conflicted, as we saw in the case of Ptolemy, too strongly with the general physical conceptions of the Greeks for it ever to advance beyond the rank of a curious mathematical fiction. A fundamental change in physics would be necessary to make the doctrine of the moving earth really fertile.

Physical astronomy was in the Greek view a matter for philosophers. Mathematicians might concoct whatever they wished if it seemed to them to favour their specific technical–astronomical purpose, but it was up to philosophers to determine metaphysically what motions actually occur in the universe. It is easily understood that they could not make much use of eccentrics, epicycles, and equants. Yet Ptolemy did devote a separate work to the possibility of realizing to a certain degree his mathematical systems of motion physically.

During the same last centuries of the pre-Christian era in which Hellenic astronomers worked out the above systems of celestial bodies with the object of compiling tables for calculating the position of a celestial body at a given point of time, this object was reached in an altogether different manner in Mesopotamia in what is usually called Seleucidan or Chaldean astronomy.*

The characteristic difference from the Greek method is that there is no question of geometrical systems of motion used to account for the positions observed, but these are represented by means of pure arithmetic. This may best be explained by an example from each of two systems used for this purpose.

In the first system, which is the simpler and is usually regarded as the older, the sun's motion is described by assuming that it passes through a specified arc of the ecliptic at a specified uniform

* This astronomy is called Seleucidan from the Seleucid dynasty, which ruled the Near East from 312 to 65 B.C. and from which the Seleucid Era is named. It is sometimes referred to as Chaldean in the sense of late Babylonian.

velocity and through the complementary arc again uniformly, but at a different velocity. The point was so to choose these arcs and velocities as to approximate the observed positions as closely as possible. In the second, more complicated system (with which the first was coexistent) a different constant velocity was stated for each month, the values alternately increasing and decreasing according to an arithmetical series. If these values are plotted in a curve, the points can be connected by a zigzag line. For this reason the Seleucidan astronomers are sometimes said to have used zigzag functions. It would however be wrong to think that there were zigzag lines on Babylonian clay tablets.

This second method was also, and in various manners, applied to the motions of the moon and the planets. It was of great practical importance to represent the lunar positions as accurately as possible in order to calculate in advance the points of time at which the crescent of the waxing moon would for the first time be visible in the western sky after sunset, this being the beginning of the new month. There were highly complicated tables for this purpose, the interpretation of which has largely, but not quite, succeeded. Jupiter was evidently studied the most accurately among planets. There are rather complicated tables for this planet from which the moment of heliacal rising and stationary positions could be read off.

It should be borne in mind that all these tables show calculated and not observed positions. The actual positions have as it were been arithmetically stylized in them. Little is known about the way in which the figures were linked up with the observations.

The fundamental difference in method between Seleucidan and Hellenistic astronomy – remarkable when it is considered that they developed at the same time in countries which had a cultural contact – rules out the possibility of the one having in any way been derived from or being a continuation of the other. This is all the more surprising because it is an established fact that the Greek astronomers took over much factual material from the Babylonians. The astronomical constants stated by Hipparchus are undoubtedly of Babylonian origin; Ptolemy also makes use of Babylonian observations.

This is the only way in which Seleucidan astronomy influenced the development of this subject. Nothing has been retained of the method of the zigzag functions. Later astronomy entirely originated from the Greek conception.

MECHANICS

This word originally signified, in accordance with the derivation (*mèchanè* = machine), the study of machines. The development of natural science, however, has resulted in its principal meaning being changed into that of a mathematical study of bodies in motion (with equilibrium as a special facet of it). This subject came into being by idealization and abstraction from the contemplation of physical bodies in motion in the same way as geometry developed from the study of their shapes and dimensions.

The most important machines known to Greek antiquity were the five simple so-called *dunameis*: lever, pulley, windlass, wedge, and screw, to which, however, cogwheels must immediately be added. An impression of the ingenious uses made of these tools and their combinations may be gained from the works of the Alexandrian mechanician Heron (first century A.D. ?). In his works a statement is already found of the general rule that against any saving of force effected by a device there is a proportional lengthening of the path over which the force has to be exerted. At a later stage of development this was to be expressed in the proposition that a mechanical device does not provide any economy of labour. The idea itself was even older: it had already found its classical graphic presentation in the story that Archimedes had invented a device which enabled him, by means of quiet manipulations, to launch a ship built for King Hieroon of Syracuse (d. 215 B.C.) but which, when lying completed on the shore, could not be budged. On this occasion he is reputed to have uttered the famous words: 'Give me a place on which to stand and I shall move the earth.' It is, of course, idle to speculate on the machine he might have used to accomplish this.

Greek science provides two examples of theoretical mechanics,

which both proved to be of great historical significance, namely two demonstrations of the rule for the equilibrium of a lever (the inverse proportionality of force and arm) which people were apparently unwilling to accept immediately as an empirical result. The first occurs in a document *Mechanics* (in fact *Mechanical Problems*) which was formerly considered to be a work of Aristotle and which in any case belongs to his school (it is nowadays attributed to the physicist Straton of Lampsacus (d. 270 B.C.), his second successor as head of the Lyceum, while the other is given by Archimedes in his work *On the Equilibrium of Planes*.

The Aristotelian deduction (Fig. 7) is based on the observation

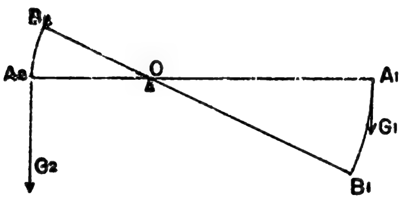


Fig. 7. Aristotle's proof of the law of the lever.

of the simultaneous shifts made by the points A_1 and A_2 of suspension of two weights G_1 and G_2 balancing each other on a lever when the bar is given a rotation round the fulcrum O. These shifts A_1B_1 and A_2B_2 are proportional to the distances of the points of suspension from the fulcrum, and as they take place in the same time, the same applies to the speeds at which the points of suspension move. The inverse proportionality of weight and arm may, therefore, also be conceived as inverse proportionality of weight and speed and that this exists may be understood from the fundamental law of peripatetic dynamics (see p. 39). To see this, each of the two weights has to be regarded as motive force for the other; a large weight at a short distance has the same effect as a small weight at a proportionately greater distance.

This reasoning is not very convincing to the reader of today;

he – rightly – has the feeling that all sorts of different concepts from mechanics are mixed up and in particular he cannot understand why time should be drawn into the question. Yet – as we shall see – this Aristotelian deduction contains the germ of an important general principle of mechanics which (bearing its origin in mind) is called the principle of virtual velocities or (rather) the principle of virtual displacements (or of virtual work).

The proof given of the principle of the lever by Archimedes is based in the Euclidean manner upon a number of preconceived definitions and axioms. These include:

(i) That a symmetrically loaded lever is in equilibrium;

(ii) that a body suspended on a lever may be replaced by another of the same weight, provided that the distance from the point of suspension to the fulcrum remains the same.

The proof then proceeds as follows (Fig. 8): At A_1 and A_2 the

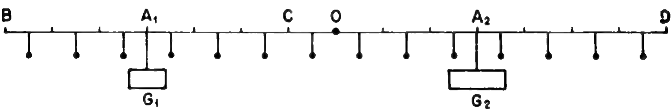


Fig. 8. Archimedes' proof of the law of the lever.

weights G_1 and G_2 are suspended from a bar rotating at O. It is assumed that $G_1 : G_2 = n_1 : n_2$, in which n_1 and n_2 are whole numbers. It can therefore be assumed that $G_1 = n_1 p$ and $G_2 = n_2 p$. It is to be proved that the lever is in equilibrium when

$$G_1 : G_2 = OA_2 : OA_1$$

It can, therefore, also be assumed that $OA_2 = n_1 t$ and $OA_1 = n_2 t$. Now make $A_1B = A_1C = OA_2$, then $A_2C = OA_1$. Also make $A_2D = OA_1$, then $OB = OD$. Now divide BC into $2n_1$ parts t and CD into $2n_2$ parts t. Replace $G_1 = n_1 p$ in A_1 by $2n_1$ weights $p/2$ in the centres of the $2n_1$ parts t, into which BC may be divided, and similarly $G_2 = n_2 p$ in A by $2n_2$ weights $p/2$ in the centres of the $2n_2$ parts t of CD. That this is permissible is vouched for by the axiom referred to under (ii) above. Archimedes apparently used as a basis the consideration that the common centre of gravity of each of the two sets of weights suspended from the bar

does not change its position on account of the division. Unfortunately we do not know which centre of gravity theory lies behind this.

The lever is now loaded symmetrically and is therefore in equilibrium according to the first axiom.

In a subsequent proposition it is proved that the thesis is also correct if G_1 and G_2 and therefore OA_1 and OA_2 are not in whole number proportion.

We shall not go into the question whether the proof reproduced above is really valid or whether the second axiom is not essentially the same as the proposition to be proved. It is at all events extremely ingenious and it was of great importance for the history of mechanics. It seemed to open the way to a mathematical approach to a branch of natural science and therefore had a strong inspiratory effect on later development. In Antiquity no further progress was made along this path. Attempts were made to trace by a similar method the so-called law of the inclined plane which gives the relationship of two weights linked by a cord slung over a pulley, each of which lies on an inclined plane. These attempts were not, however, successful.

Mathematical treatment of problems such as those discussed above is of course only possible if the position is regarded from the start as ideal – no account being taken of friction, air resistance, and other factors causing the relations which have been found to be not exactly valid and the values of the weights balancing each other on a physical lever or on physical inclined planes to vary within certain limits. All these things reveal the strong mathematical strain of Greek scientific thought.

Followers and commentators of Aristotle have supplemented and modified his views on the motion of falling and projected bodies. They knew that the falling movement is an accelerated motion and wondered how this came about. Straton undoubtedly discussed this in a work *On Motion* which has not come to us, and it is unfortunately not possible to do much more than conjecture as to his contributions to this subject. One such conjecture implies that he held the instantaneous speed of a falling body to be proportional to the path covered since the motion started. He

very probably rejected the distinction between light and heavy bodies that occupied such a fundamental position in the Aristotelian system; all bodies are heavy and by nature therefore drop downwards. The case may, however, arise that they are forced upwards by other heavier bodies and then appear to be light. It is questionable whether absolutely heavier was sufficiently distinguished from specifically heavier. Similar views seem to have been held by the astronomer Hipparchus in a work *On Bodies which are drawn downwards by their Weight.*

Of great historical importance are the considerations which the commentator Philoponos (first half of the sixth century A.D.) devoted to fall and projection. On the basis of experience he contradicts the contention implied in the Aristotelian Law of falling bodies that the heavier the body the faster it drops; for bodies which do not differ very considerably in weight, the falling times are found not to differ perceptibly over a given distance. He also rejected the theory which seeks the driving force of a projected body in the surrounding medium; he wished to regard the driving force linked to the projectile as an immaterial motive power which the projector has imparted to the body by the action of projection. This view will recur in the impetus theory of the scholastics.

HYDROSTATICS

In the sphere of hydrostatics Antiquity provides us with the law of the upward force which a body experiences when it is immersed in a liquid. This is still named after Archimedes, who discovered it. He deduced it in his work *On Floating Bodies* by the same method by which he proved the law of leverage, i.e. on the basis of preconceived definitions and axioms. The axioms are however now less convincing; they are derived from Aristotelian physics and are therefore not acceptable to the reader of today. It is typical of Archimedes that he really only used the law as a starting point for very complicated mathematical investigations of stable floating states of paraboloids of revolution.

In Antiquity it was also used incidentally to determine the

specific gravity of a substance. Although it provided strong support to the opposition to the concept of lightness which we have seen expounded by Straton and Hipparchus, there was no question of this concept being generally rejected. On the contrary, it remained for centuries an unassailable element of physics.

OPTICS

It tallies with our above remarks concerning the mathematical turn of Greek thought on nature that geometrical optics came into being after all geometry of light rays. The equality of the angles of incidence and reflection on a mirror was already known in early times. Heron notes in this connexion (Fig. 9) that to

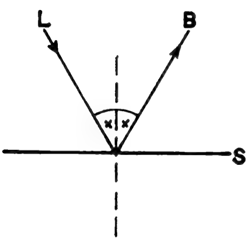


Fig. 9. Heron's principle. To go from L to B via the mirror the ray of light takes the shortest path.

come from a point L by reflection on a plane mirror S to a point B, light follows the shortest path from L to B via the mirror. Here we meet the oldest example of one of the so-called extremum principles, which were, as we shall see, to play such an important part in physics in later times, and which were often connected with the consideration that Nature operates in the simplest way possible. There are also theories regarding parabolic and spherical mirrors. These do not take us far; exact mathematical treatment is difficult here and the thought of an approximative theory does not seem to have occurred to the Greeks.

The theory of refraction of light was distinguished as dioptrics from that of reflection as catoptrics. Here the fundamental phenomena are known. Ptolemy gave results for complementary values of the angles of incidence and refraction, without, however,

establishing the correct functional relationship between the two. The regularity of the figures which he gave is too great not to be mistrusted a little.

As for a practical application of mirrors there is a story that, during the siege of Syracuse by the Romans, Archimedes set fire to the enemy's fleet by concentrating reflected sunlight on to it by means of mirrors. Much has since been written on whether and how he might have done this.

Various writers devoted much attention to the question of how sight comes about. According to the most widespread theory, that of visual rays, rays leave the eye and scan, as it were, the bodies to be perceived and thus provide an impression of them. The Atomists assumed that we see these bodies because they transmit images (*eidola*, *simulacra*), which penetrate into our eyes and then awake sensations. According to another theory, which is also atomistic, these images do not enter the eye themselves; this is done by a copy which they have made in the air condensed by the effect of the sun. In the theory of the *synaugeia* Plato made rays coming from the eye mix with effluxes of the bodies; a bridge is thus formed between the object perceived and the organ of sight, which is influenced by the former and awakens perception in the latter.

Aristotle rejected the view that something physical had to move between the object and the eye. According to him sight consists of an effect of the object on the organ of sight through the medium, the diaphanous nature of which must, however, first be actualized by luminous substances (fire and ether) to be able to perform its function. The actual diaphanous medium can then transmit the effect of the objects' colours to the eye. The colours are the real cause of the bodies becoming visible, while the light only brings into being the conditions required for this.

A stoic theory held that out of the central organ of the soul (the *hegemonikon*) comes a *pneuma* of sight, which enters the outside world through the pupil of the eye and causes a state of tension (*tonos*) in the air between eye and object. By means of this tensed air the eye then scans the objects, thus receiving an impression of their shape.

PNEUMATICS

This embraces all phenomena which physics in later times was to explain by means of air pressure. Much the most important question is the question of the possibility of a vacuum. To that question Aristotle had given a categorical negative. For the most part his view were followed in this respect, at any rate as far as *macro-vacuum* is concerned – a coherent empty space of perceptible dimensions. As arguments for the palpable impossibility of this, phenomena such as the working of the pipette or plunging siphon (*clepsydra*), the cupping-glass, and the siphon are principally mentioned. That a liquid rises up against its nature in these devices is readily grasped by the consideration that otherwise a vacuum would be formed between air and water and that Nature obviously does not allow this. In the atomistic view of the cosmos, however, it was necessary to assume the existence of a *micro-vacuum*, an empty space between the atoms, because otherwise the atoms would have no room to move. Numerous applications of pneumatic effects, in which thermal phenomena are also used, were dealt with by Heron. The best-known example is the *aeolipyle*, a rotatable mounted globe from which jets of steam spouted, causing it to revolve.

ACOUSTICS

Here, too, a mathematical and a physical branch may be distinguished. The first consists of rather complicated theories of musical intervals and the scales and genera containing them (namely the diatonic, the chromatic, and the enharmonic). This is more important for the development of musical theory than for that of science and we shall not, therefore, consider it further. The second branch is concerned with attempts to understand the propagation of sound in air and the difference between high and low notes. No concrete results of permanent value were obtained. There are indeed reflections which seem to describe the spread of a longitudinal wave in air, and others in which high notes are

related to rapid movements and low notes to slow ones, but in this latter case we realize again and again that the speed at which the particles of a sound-producing body vibrate was confused with the speed at which the disturbance of equilibrium aroused in the air spreads.

METEOROLOGY

This word is derived from *τὰ μετέωρα*, which means 'the things in the air', and the subject embraces all phenomena which occur in the atmosphere or which are thought to take place there. It therefore involves comets, meteors, the rainbow, haloes and parhelia, rain, snow, hail, dew, hoar-frost, thunder and lightning, etc. Physical geography and petrography also come within the sphere of meteorology.

The best-known work in this field is the *Meteorologica* of Aristotle, the fourth book of which, however, dealing not with meteorological aspects but with various physical–chemical processes such as maturation, decay, boiling and baking, melting and congealing, etc., was not written by him personally. It is surmised that here too we are confronted with a work by the physicist Straton.

In meteorology proper the treatment of the rainbow and allied atmospheric phenomena deserves attention. Aristotle and his commentators attributed all these to the reflection of sunlight, either in droplets of water or in a whole concave cloud. There are indications, however, that attempts had already been made in Antiquity to include refraction in the explanation.

ELECTRICITY AND MAGNETISM

Of these two branches of natural science, which in our days are so much to the fore, only the two most elementary phenomena were known in Antiquity. These were that rubbed amber makes light objects move, and that a piece of iron moves towards magnetic iron ore. Neither of these phenomena was put to further use. Yet the fact that they were known is not completely unimportant.

The Greek name for amber (ἤλεκτρον) has given electricity its name, and astonishment over the magnetic phenomenon led Thales to speculative considerations on a soul lodged in the magnet, which moved the iron. This notion was to find much support later. It certainly contributed to the fact that from Antiquity onwards we always find the statement that the magnet attracts iron (and not, for example, that the iron is driven towards the magnet), although observation reveals nothing to point specifically to an effect produced by the magnet, as the word 'attraction' suggests.

CHAPTER 4

Greek and Roman Engineering and Technology

In contrast with the break which may be observed between Greek and pre-classical science there was no such gap between pre-classical and classical engineering or technology. This does not, however, mean that the Greeks and Romans did not contribute original ideas and inventions, but simply that both were based on a technology limited by the use of human or animal energy and hence limited in the size of the machinery and the objects it could handle and work. Moreover, as the pendulum of civilization swung west and Greece, and later Rome, became the dominating factor in world politics, certain branches of engineering became more important than in earlier days. The Hellenistic kingdoms and the Roman Empire laid much more stress on public works and communications than earlier empires and thus we find great activity in these fields and less in others.

MILLS AND PRESSES

Other factors were at work too. There was a great contrast between classical agriculture and that of the ancient Near East. Whereas the latter depended mostly on irrigation and hence on the art of conducting and storing the waters of the rising rivers, the former rarely used irrigation techniques and depended on the conservation of the winter and spring rains in the top soil layers to last over until the parching summer months. This involved different techniques and equipment. The Hellenistic engineers helped to mechanize the arduous task of raising water to the higher grounds in Egypt and Mesopotamia by constructing better and more elaborate machinery such as the wheel of pots, the compartment wheel, and the Archimedean screw, which was first used in Egypt in the days of this great mathematician. Such

machinery was not in common use in the classical world until the Arabs introduced irrigation techniques into western countries to grow rice and other foodstuffs needing much water. The classical farmer grew wheat and barley, but gradually specialized in producing olive oil and wine which he exchanged for corn in Egypt, Africa, Spain, or Gaul. Both olive oil, his main source of fats, and wine required special equipment.

The Greeks had closely studied the cultivation, grafting, and propping of the vines, but they also materially improved the quality of their wines by better pressing techniques. In the Near East the best type of press available had been the bag press, that is, the grapes, which had previously been subjected to treading, were placed in a bag which was then wrung by torsion. A much more efficient form of press, the beam press, was invented in the Aegean world probably as early as the second millennium B.C. It applied the principle of the lever, the end of a heavy beam being hinged in a wall or between two strong stone pillars and the other end being loaded with a heavy weight. The middle of the beam pressed down a stack of bags with olives or grapes, and by applying extra weights more than one pressing could be obtained.

The Roman engineers of the first century B.C. and later improved this beam press by inventing methods of dragging down the end of the beam by means of ropes and pulleys or screwing it down, thus enabling the vintner to apply varying forces on the press. They also invented the screw press, which either exerted its force directly on the mass by means of a screw held by a frame and forcing down a lid on the press-bed much like the modern copying press, or two screws on the end of a beam screwed it down over the mass to be expressed as in a cloth press. A third type of press invented by them was the wedge press, in which wedges were forced in between the stack of bags of olives or grapes held by a frame. The beam presses were used for olives and grapes; the screw and wedge presses were gradually applied more particularly to oil seeds, sheets of papyrus, cloth, the manufacture of oils from herbs and roots, and in the preparation of essential oils.

The rotary querns introduced from the East were also improved. The commercial donkey-mill of the Romans consisted of an hourglass-shaped upper stone turning over a conical lower stone. The energy was at first supplied by two slaves or a donkey or mule, later by water power. The hand mills were also materially improved by the Romans and they seem to have invented the small wooden pepper mill, the ancestor of our coffee-grinding apparatus.

WATER SUPPLY

The ancient inhabitants of Armenia had resorted to water tunnels driven into the hillside to catch subterraneous water for the irrigation of their fields. The Assyrians had elaborated this into the earliest type of aqueduct. Thus Sennacherib, like his father Sargon II, intended to extend the land under cultivation by bringing down water from the mountain streams, pent-up rivers, and adits driven into the hillsides. In 703 B.C. he built a large aqueduct to water the region between Niniveh and his palace of Chorsabad. The adit or *qanât* survives until the present day in Armenia, Iran, and other Eastern countries to water the fields, but in the hands of the Greek engineers it was turned to a different use.

Water supply systems for the cities had already been built in Mycenean Greece and, as the Greek doctors stressed the importance of good water for the health of citizens, the ancient Greeks built aqueducts to supply their cities with good drinking and bathing water. One of the earliest of these was the aqueduct of Samos built about 530 B.C. by Eupalinos and including a 1100-metre-long tunnel. True, King Hezekiah had built a long tunnel to the spring of Siloah in his city of Jerusalem about 700 B.C., but such 'water tunnels' in the East were protected approaches of a well outside the city wall rather than conduits of large quantities of water into a city like the Greek and Roman aqueducts.

The Greek engineers learned the use of the siphon to cross a deep valley between the water source and the city, and they were well aware of the cost of such high-pressure leaden conduits protected by hollow tree trunks or stone. They would rather resort

to the bridging of valleys for the aqueduct channel if this was cheaper, but siphons had to be applied now and then, for instance in the case of the aqueduct of Pergamon (179–159 B.C.). The Romans carried the aqueduct system to perfection, leading the water through settling tanks into *castellae* or water-towers in the hills near a town and distributing it to the houses, baths, and fountains as required. The consumption of the Roman householder was controlled by a delivery tube of the Venturi-type branching from the main line into the house and providing the authorities with a means of raising money on the quantity of water delivered. These delivery tubes are amongst the earliest standardized pieces of equipment, their dimensions and capacity being fully laid down in regulations. The control and testing of water was well understood in ancient Rome and the aqueducts were constantly inspected, cleaned, and kept in repair by specialists.

BUILDING

The importance of a good sewer system was fully understood in the classical world. The older cities from the Indus valley to Egypt had elaborated good systems of sewerage which had been taken over by the Aegean world and applied in Greece and Rome, where public health was a task laid on the shoulders of special authorities. In fact, water supply and public hygiene were far better in the classical world than for many a century later in western Europe, where the standards of Imperial Rome were not surpassed until the end of the last century.

Classical architects developed their own forms of architecture, which required new tools and machinery. Though the Assyrians had known the pulley about 800 B.C., it never played a large part in building. In the classical world, however, cranes moved by hand and foot were used to raise the columns decorating the temples and public buildings. The theory of such cranes was supplied by the experts on mechanics, and the practical engineers like Vitruvius Pollio (*c.* 50–26 B.C.) describe different types evolved. Lime mortar came into common use and the Romans discovered

natural trass near Pozzuoli about 150 B.C. and later in the Eiffel (Germany) which proved an excellent mortar, setting even under water. They mixed it with sand and stones to form concrete, which was used for the cores of the large public buildings and covered with slabs of coloured marbles. Metal clamps were widely used to connect blocks of natural stone.

LAND TRANSPORT

Land transport also made great strides forward in the classical world. It had meant little in the pre-classical world, when caravans of pack animals trudged slowly along the well-beaten tracks which were sometimes provided with road signs. The only material addition to the means of conveying goods over larger distances was the taming of the camel, or rather the dromedary, which the Assyrians introduced about 700 B.C. for trans-desert transport. The Persian 'kings of kings', however, ruling an empire built up of so many different nations, started out to weld it into a whole. One of their policies was to improve the means of communication in order to get a better grip on their empire.

They began to clear tracks, to repair bad places, to build bridges where fords were impossible, and to build a chain of post houses, where fresh horses were available for the messenger service which they instituted and which kept them in close contact with the provincial capitals. In certain cases the stations along these roads had barracks with soldiers to ensure safe traffic in the region. The Hellenistic kings of Egypt, Syria, and Asia Minor copied and improved this traffic system and the Romans took it over and added further details to this governmental mail and passenger service. This *cursus publicus* was also available to the general public under certain conditions, for instance the traveller had to obtain a permit or 'diploma' from the authorities and the maximum load of different types of vehicles was carefully regulated.

The Roman road system was fundamentally different from its predecessors. The ancients had in certain cases covered the surface of their city streets with slabs of natural stone; so had the Greeks, who also resorted to levelling the track and cutting

artificial wheel ruts into the rocky soil. The Romans, however, made artificial roads laid in an excavated trench as far as possible, and consisting of a well-designed set of four layers, constructed in such a way that proper drainage protected the actual road surface from disintegration. Thousands of miles of such roads opened up not only the countryside of Italy but also the newly conquered provinces of Europe and the Near East and provided the marching armies and the caravans of merchants and their pack animals with safe and good roads. Never had the speed of travelling been so high as in Roman days, nor was it exceeded until the times of Napoleon and the advent of the railways.

Certain technical difficulties still impeded the growth of mass transport on these improved roads. The ancient manner of harnessing an animal might have been adequate for the slow-moving ox; it was unsuitable for the mule and horse which were throttled by it and could exert only part of their energy to pull heavy loads. Neither was the art of harnessing strings of animals in tandem properly understood. Hence mass transport was expensive and goods were still transported as directly as possible to the nearest harbour to be shipped by sea and river. On the other hand, travel was greatly facilitated by road signs and milestones and by the compilation of itineraries and road maps, the need for which had also stimulated the rise of cartography and geography.

WATER TRANSPORT

Transport by sea also improved greatly. The early empires had used different types of rafts and river craft, which in the case of Egypt were wooden composite copies of earlier reed boats and in the case of Mesopotamia built-up canoe types of ships, neither of which being very seaworthy. Hence such ships as sailed the sea tended to hug the coast as much as possible, and this remained a custom for many centuries during the classical period. However, the Homeric ships were already wooden ships with keels, stem and stern posts, and ribs (frames or timbers) covered with outside carvel-built planking, that is, their planking met edge to edge. Large and more elaborate types such as the bireme, trireme, and

quinquereme were developed to increase speed and enable the merchant to cross such straits with strong currents as the Dardanelles to reach the rich wheat country of the Crimea and Southern Russia. These names probably indicate the number of men employed on each single row of oars rather than the number of rows of oars. The Mediterranean galleys also used sails. Gradually oared warships such as the light galley and the heavy galleon began to be differentiated from the sailing merchantman.

Different types of sea-going sailing ships were evolved, as well as a river barge, built without a keel from heavy floor-timbers pegged to large knees which in turn were fastened to a heavy stringer giving the barge its longitudinal strength. Such barges were more or less standardized all over the classical world and supported a busy river transport of wine and corn. Moreover the Hellenistic and Roman engineers perfected the earlier Phoenician attempts to build moles and artificial harbours and created famous ports such as Alexandria and Ostia. In earlier days the fires of the Temples of Neptune built on promontories had served to guide the sailors. Then lighthouses, such as the famous Pharos of Alexandria and the Tower of Hercules of La Coruña, were built. The larger ports had docks where ships a thousand tons and larger were built and repaired.

MINING AND METALLURGY

The classical world is more or less synchronous with the earliest phases of the Iron Age. Meteoric iron had been known for centuries, but its relation to iron ores, already used as pigments, was unknown. By 1500 B.C. the smiths of Armenia had found the proper method of producing iron from these widespread coloured iron ores. Iron metallurgy was completely different from that of copper and its alloys. No longer was the molten metal produced by reducing certain (sometimes pre-roasted) ores with charcoal and then cast in certain forms or alloyed by a second smelting with other ores or metals in order to produce a specific alloy most appropriate for the requirements of the finished product. Iron metallurgy required higher temperatures and first yielded a

spongy mass of cinders and small particles of metal. By repeated heating and hammering the cinders were evicted from the bloom and the piece of wrought-iron produced could be 'steeled' by making it absorb carbon in a charcoal fire. The properties of the steeled wrought-iron could be governed by carburizing, annealing, tempering, and quenching. Certain ores were suitable for the direct production of steel by a crucible process. This 'wootz' steel of the Indian smelter was imported into the Roman Empire as 'seric (Chinese) iron' until its secret came to the West in Arabic times. It took the smiths of the classical world more than ten centuries to master the new techniques of iron metallurgy and to invent the appropriate tools and furnaces. They did not yet possess anything equivalent to our blast furnace and were unable to produce pig-iron and liquid cast-iron. In fact, when cast-iron was formed by fortuitous circumstances it was thrown away.

The change-over from copper and its alloys to wrought-iron and steel was of great importance. As bronzes had always remained expensive because of the scarcity of tin in the Old World and as they were no harder and cheaper than certain polished stones, stone tools and equipment had survived in many a trade. Now, as iron ores were abundant all over the ancient world, metal came more in demand as steeled wrought-iron proved better in most cases than the stone tool, for instance for plough shares. Iron has therefore truly been called the democratic metal in contrast with the 'aristocratic' copper and bronzes, for it provided the ordinary craftsman with better tools to do a more efficient job. Metal now began to conquer the world and to supplant the still-surviving stone or flint tools and weapons. In the Mediterranean region the gradual deforestation by goats was now hastened by the expansion of iron metallurgy. The price of timber rose slowly but ominously and so did that of charcoal. However, the classical world was still very much an agricultural world in which the mines and smelting sites were islands in a sea of fields and meadows.

The Greeks and Romans added only two new metals to those of earlier generations of smiths and metallurgists. The Greeks

learned to produce brass by 'cementation' of copper bars by heating them while they were embedded in charcoal and powdered zinc ores. This process probably originated in the Armenian mountains in the early first millennium B.C. but did not become important until the turn of our era. The Roman metallurgists started to produce mercury on a fairly large scale in Spain; it was used to extract and refine gold and silver.

However, the relation between surface indications and strata of ores deep down in the earth was better understood and large-scale production of ores and metals was sponsored and even undertaken by the state. In Spain the Romans extracted the gold ores of the Basque provinces by breaking up the gold-bearing strata by hushing (by the impact of water), for which purpose they built large aqueducts. They also introduced the amalgamation process of extracting such ores. Impure copper and other metals were alloyed with lead; when the alloy was heated at low temperatures the lead would drip out and entrain the silver and gold. This 'liquation' of base metals was applied to the copper ores of Spain by the first century B.C.

The Greeks had already perfected the extraction of silver from lead and lead ores, for instance in the famous Laurium mines near Athens. But, whereas the Greeks could desilver their lead up to ·02 per cent of silver, the Roman smelters brought this limit down to ·002–·01 per cent and managed to produce silver from the Greek slags at Laurium. The art of cupellation or oxidation of the base metals, which had been applied to precious metals since 1500 B.C., was perfected. Together with the touchstone it served to test the purity of gold and silver objects and coins and hence it played an important part in the alchemist's laboratory. Coins (stamped and guaranteed standard portions of silver and gold or copper) came to be used instead of weights and bars of precious metals and dominated trade from the sixth century B.C.

The Romans started to produce tin on a much larger scale in Spain, and this led to the abandonment of mines in Brittany. At the same time tin was produced locally in Cornwall from 500 B.C. onwards and it became an important factor in international trade. Even when alluvial tin gave out and the metal had to be produced

from vein ore in the third century A.D., Cornish tin won the day and the production in Lusitania and Gallicia declined quickly after the second century A.D.

Large quantities of copper were produced, not only in the ancient centres of Cyprus and Asia Minor but also in Tuscany, the eastern Alps, and Spain. The use of proper fluxes and the working of intermediary products such as black copper were well understood. The production of copper ores was limited by subsoil water and hence large pumping installations using compartment wheels driven by treadmills were installed in the Spanish mines to reach lower strata. Roman copper and bronze were even exported to the German tribes in the north and to India in the form of coins and bars.

Iron was produced in a greater number of centres, as iron ores of good quality were abundant. Nevertheless, certain centres like Laconia, Tuscany, Gaul, and Spain were famous for their products, and the steel from Carinthia, which was worked in the cities of the Po valley, was most important to the Roman army.

WAR ENGINES

The Assyrians had introduced siege-engines in their armies. Following this example the Hellenistic and Roman armies had become highly mechanized and this is the field in which the ingenuity of the ancient engineer is most obvious. This mechanization was initiated during the wars which the Sicilian Greeks waged against Carthage. Apart from the usual siege-engines like rams new forms were developed. From a primitive form of crossbow the mechanized bow or 'catapult' and the mechanized sling or 'ballista' were developed. As early as 400 B.C. Dionysios of Alexandria is said to have invented a kind of 'machine gun', a catapult able to fire a series of arrows stored in a magazine. Batteries of catapults helped Dionysios the Elder of Syracuse to beat off the attacks of Himilko on Motye (397 B.C.).

Both Phillip of Macedonia and his famous son, Alexander the Great, promoted the mechanization of warfare. The famous

engineer Diades helped to shorten the siege of Tyre considerably. In the chronicles of the Macedonian kings we frequently read of barrages from such engines used to cover attacks or retreats. Several engineers like Aeneas Tacticos (*c.* 300 B.C.), Ktesibios (*c.* 250 B.C.), Philo of Byzantium (*c.* 250 B.C.), and Heron (*c.* A.D. 100) wrote special treatises on such engines. Most of these engines relied on the tension of bundles of tendons or ropes to propel the missile; the elasticity of springs and of compressed air, though often considered, was not yet sufficiently mastered.

After the siege of Carthage no fewer than 2000 catapultae were captured. The Roman army used such *catapultae* and *ballistae* in large numbers, attaching them to carriages and thus forming easily transportable batteries of '*carroballistae*'. They also had their specialists on such engines. Vegetius's handbook enumerates many forms of mechanized siege-engines, artillery, and methods of fortification. In this field we find the only attempts to calculate such machines. Thus Philo gives us an empirical formula relating the size of the bundle of tendons in the catapult to the weight of the missile propelled. This machinery was most effective and lasted for several centuries after the invention of gunpowder.

ENGINEERS AND CRAFTSMEN

The classical engineers demonstrated their mastery of the simple machines at their disposal: the wheel and axle, the lever, the pulley, the wedge, and the endless screw, which they combined with great skill to more complex machinery. Unfortunately, those in authority were not interested in mechanization except in certain fields like mining, war engines, and public works. The plans to harness the forces of nature which the engineers proposed in their handbooks were not supported by public money, nor were the scientists or 'philosophers' interested in the efforts of these superior craftsmen. In fact, Plutarch reports that Archimedes was ashamed of the engines he constructed for the Syracusans to beat off the Roman invader. Science was not yet aware of its task to assist the engineer in conquering the forces of nature for the common good, though on several occasions the engineers of

the Later Empire expressed the need for a scientific background in the education of future engineers.

Only one force of nature was effectively harnessed in Antiquity, the force of running water. During the first century B.C. the attention of the Roman engineers was drawn to a kind of primitive water turbine, which was in use in the Armenian mountains and which has survived to the present day in Central Asia, the Balkans, Galicia, the Shetlands, and Scandinavia. The peasants used it to move a set of millstones for grinding their corn. The Romans converted this into a much more elaborate and efficient piece of machinery, the water-wheel, the earliest forms of which produced some 3–5 h.p., i.e. six times that of the original.

Here then was a prime mover capable of taking over the tasks of men or ill-harnessed animals moving machinery and also allowing the construction of larger, more powerful machinery. However, several factors conspired to slow down its introduction. Few Mediterranean rivers had sufficent water all the year round to allow an economic use of water-wheels, and most ancient water-wheels were run by an artificial water supply from a costly aqueduct. Many ancients believed the forces of nature to be the domain of supernatural power and saw in their harnessing an act of blasphemy. Neither was there that concept of charity which prompts us to shift the heavy burden from man and animal to the forces of nature. But, above all, ancient economy was not yet prepared to absorb mass-produced goods except in very few cases. There the water-wheel actually found its place. Notwithstanding the resistance of persons with vested interests, who claimed to fear idleness and unrest among the slaves and workers, during the first centuries of our era the water-wheel came to run the corn-mills of Rome, Athens, and other big cities and in centres of military activities like Barbegal near Arles in southern France. However, its introduction was slow and did not stimulate mechanization until centuries later.

TEXTILES

Developments in most crafts were hardly stimulated by mechan-

ization, for in many cases such crafts were home industries with small outputs and seldom full-time jobs carried out in shops or anything like our factories. This applied, for instance, to the textile industry, which both in Greece and Rome remained a home industry even in the Imperial period. Emperor Augustus still prided himself on the fact that his wife and daughters spun and wove the cloth for their dresses, and indeed large numbers of Romans did so, even if in the richer households special slaves were entrusted with such duties. In fact we find no organizations of spinners or weavers of any importance, the only guilds which manifested themselves politically in ancient Rome being the fullers and the manufacturers of patched quilts. The former bought the home-made cloth from the homes and fulled, dyed, and finished it for sale in their shops; the latter collected and bought rags and turned them into the patched quilts used by the slaves and the poor and also serving to extinguish fires.

Hence there was little development in the methods of spinning and weaving. The horizontal loom, probably hailing from Egypt and the vertical loom, possibly invented in Syria and common in the classical world together with the warp-weighted loom characteristic of prehistoric Europe, were universally used but limited the weaver to certain simple weaves such as rep, tapestry, tabby, and gauze. However, the weavers were no longer restricted to wool and linen, for new fibres had come to stimulate the development of new techniques more suited to their properties. Cotton had been known for centuries in the Indus valley and spun and woven with the help of special techniques, until the Assyrian king Sennacherib introduced the 'trees bearing wool' as a rarity in his Chorsabad palace garden around 700 B.C. This was but a temporary meeting with a new fibre which became much better known in Hellenistic times when Alexander the Great and his successors were in direct touch with India. Cotton fabrics were, however, first produced locally in the present Sudan a few centuries B.C. Cotton came to be grown on a modest scale in Egypt, Palestine, and Syria, but the real impetus came only in Islamic times. Up to the eighteenth century the weavers had great difficulty in obtaining a strong cotton warp thread and hence they

produced cloth with a linen warp and a cotton weft, which was later called 'fustian' after a suburb of Cairo. Cheap cotton goods were imported from India, Bahrein, and the Sudan from Hellenistic times onwards, but the home-produced cotton stuffs called 'caibasus' were mixed linen/cotton weaves used in the ancient world for sails, awnings, and curtains.

Though in the days of Aristotle a wild silk called 'bombyx' was produced in the island of Cos and other places in Greece and Syria, the ancients became better acquainted with the true Chinese silk, called 'serica', in Hellenistic times, and during the Roman Empire silks were imported and often rewoven at Alexandria and Syrian centres such as Palmyra to suit the tastes of the rich. Sericulture as such dates back to the days of the emperor Justinian, when monks smuggled silkworms and mulberry leaves in hollow canes from Central Asia to Byzantium (A.D. 552), where its manufacture remained a well-protected state monopoly.

New fashions and new fibres demanded new techniques and new dyes. The expensive purple dyes were extracted from whelks living on the coasts of Syria and Asia Minor. This production of dyes was often combined with the raising of sheep in the hinterland and several towns in the Eastern Empire strove to maintain the monopoly of specially dyed wool or woollens. Better understanding of dyeing techniques stimulated the rise of chemistry. New weaving techniques to suit the fibres and new tastes were invented in Syria and Mesopotamia during the second and third centuries A.D. The addition of a third harness to the horizontal cloth loom allowed the production of weft twills in woollens. Soon afterwards drawloom weaving was invented, which allowed the reweaving of imported silks to suit local taste. In these regions the manufacture of textiles rose to an industrial stage much earlier than in the West.

GLASS VESSELS AND WINDOW-PANES

The Assyrians and Egyptians had discovered recipes for the manufacture of coloured glasses, threads of which were moulded

into multi-coloured small receptacles. However, glass became a much more important material when glass-blowing was discovered in Syria during the first century B.C. This production of hollow glass wares by skilful manipulation of a 'paraison' or bulb of glass at the end of a metal pipe opened up new horizons for the application of glass. New shapes could be produced much more cheaply, and on a large scale glass vessels, bowls, and flasks began gradually to displace ceramic and pewter household goods. This mass-production of glass table goods started in the Near East in the third century A.D. after Constantine abolished the taxes oppressing the glass-blowers. This did not extinguish the older techniques of sandcore and mould-pressed glasses, as the vessels thus produced still figured largely in the perfume and cosmetics trade.

In the West glass was appreciated earlier, for during the first century A.D. glass tableware began to vie with the more expensive silver flagons and dishes. Not only were new glass houses founded at Alexandria, but Syrian and Jewish glass-blowers settled in the neighbourhood of Rome and glass production had begun in Italy by A.D. 20. Glass houses spread through Italy to the banks of the Rhine and Gaul. Apart from the cheap free- and mould-blown wares new decorated glass vessels became fashionable. The well-developed art of gem-cutting stimulated the application of cutting techniques to glass. Not only was glass tooled when warm; it was engraved, or drawn glass threads were applied to the vessel, when both were warm.

However, apart from its use as tableware, glass also proved very useful for other applications. Glass mirrors began to oust polished stone or bronze mirrors during the Later Empire, first in the form of dark glass slabs, then as slightly convex octagonals, the back of which was covered with sheet lead. More important, however, was the production of glass window-panes. Early windows were closed with shutters or mats, or with lattices of pottery or stone, with marble, alabaster, and mica slabs, fish bladders, and oiled parchment. Glass window-panes were much more efficient, though the earliest panes were but small slabs of some 1 ft × 2 ft at most. In the villas of the rich and, above

all, in the baths they became popular during the second century A.D. and they were most useful in the northern countries, where there was a definite need to protect the householder against the rigours of the climate.

TECHNOLOGY IN THE HOME

It is strange to find that, except for glass window-panes, little attention was given by the classical engineer to improve living conditions at home. Of course ancient life was mostly enacted in the open, but the possibilities of producing light and heat were realized far later than the achievements in other fields. The ancients employed few sources for lighting: the fire, torches, and rushlights, the *candela* (a primitive candle made by dipping the wick of rushes in tallow), and the bronze or pottery oil lamp burning fats and oils. Christianity brought the beeswax candle into use by the third century A.D. None of these sources could be used for more than distinguishing objects in the immediate neighbourhood; they had nothing like the candlepower of modern lamps. Daily life therefore depended mostly on the sun. Streets were lit by the lamps in shops or over the doors of private homes. There was no street lighting before the town of Antiochia introduced it in A.D. 450. Lanterns existed only to protect the oil lamps with which the slave lit the way for his master; they were not further developed and larger amounts of light could only be obtained at great expense by having torch-holders and candle-sticks to hold many single lights, or rings of bronze to carry a series of single lamps.

In the same way heating devices remained very primitive. The open fire in a hearth in the middle of a room, or charcoal braziers, and small stoves helped to tide over the few really cold days in the Mediterranean region. As classical civilization spread north of the Alps these means of heating the home proved barely sufficient. Only in the case of the larger public buildings was a solution found. Here the 'hypocaust', a type of central heating, was adopted. It had been invented by Sergius Orata about 95 B.C. for the heating of the fish and oyster ponds in his villa at Baiae on

the shore of the Lucrine Lake. The principle of hypocaust central heating consisted of conducting the combustion gases from a wood or charcoal fire underneath the hollow floor and through the hollow walls of the space to be heated. Secondary air could be introduced into the system to complete combustion and to regulate the temperature. Since the turn of our era this system was principally used to heat the public baths in the region south of the Alps, but in Gaul, Germany, and Britain it also came to be used for large palaces and military stations, and even for the villas of rich landowners; but more modest houses were deficient of better heating systems.

Ice could be collected and transported over large distances to be stored in underground cellars until use, but such niceties were for the few only. It was not yet possible to cool drinks and food on any large scale and preservation by freezing was unknown. Still the engineers constructed some ingenious vessels for the heating of wines and food. Double-walled pottery or metal vessels allowed the circulation of hot water kept at the right temperature by a brazier or charcoal fire, and similar vessels could cool drinks efficiently.

Though the Gauls had invented a kind of crude soap by boiling fats with natural soda, the only detergents used on a larger scale were crude soda obtained from deposits in Egypt or from plant ashes or decoctions from certain herbs and plants. Oiling the skin and scraping it with the strigil amidst abundant ablutions with water, or taking hot and cold baths were the only proper means of washing the body.

Other chemicals such as nitre, caustic soda, alum, acetic acid, were prepared on a small scale in a fairly pure state, but here again the demand was so small that no large industrial production developed. Even in writing materials there was little progress. True, the monopoly of Egypt in the production of rolls of papyrus was broken in Hellenistic times. Pergamon and other centres started to produce sheets of parchment, a writing material already known for centuries, and this led to a new form of book, the 'codex' or bound sheets of parchment, which was characteristic of early Christian literature. Even the very ink used in

Antiquity, a type of 'Chinese ink' composed of carbon black suspended in a gum solution, was not superseded by our gall-iron type of ink until the seventh century A.D.

These few examples must suffice to point out that, though the ancient craftsmen could produce many types of household goods, their production did not change much during the centuries, as small-scale production held few incentives for inventors and innovators except in those cases where strong forces such as the state stimulated and guided better means of production.

CHAPTER 5

The Rise of Astrology and Alchemy

WHEREAS the origin of most sciences goes back too far for us to trace it, we have at least some indications about the rise of astrology and alchemy, both of which found their origin in a well-defined historical period. Whatever our present attitude may be, as historians of science we cannot deny that both astrology and alchemy were undoubtedly sciences for many generations of students of the mysteries of the sky and of matter.

PRE-CLASSICAL ASTROLOGY

For many centuries astrology was a form of applied astronomy and stimulated its development. Astrology was born in Mesopotamia, and not in Egypt as Greek tradition would have it. We have seen that Egyptian astronomy was not so fully developed as that of Babylonia, which was prepared to support the calculations of the astrologist. Astrology as we define it nowadays attempts to prognosticate the character and future of a person from his 'horoscope', from the relative positions of the sun, moon, planets, and stars at the time of his birth, or of his conception, 279 days earlier. This is a comparatively late development, for there was a much more primitive form of astrology, 'judicial astrology', which dates back to early Sumerian times.

The Sumerians practised the art of divination from the form of the liver or the intestines of the animals offered to the gods (haruspicy), from the shapes which molten lead took when poured into water (a kind of geomancy), and many other forms of omens. They also watched the meteorological and celestial phenomena and believed that haloes of the moon, comets, and rainbows could tell them something about the prospects of the harvest, impending plagues, wars, and the like; in short that they forewarned mankind about the near future of country and state.

What each of these phenomena was supposed to foretell was written down in series of cuneiform tablets which were constantly revised and amended. About 1000 B.C. the Assyrian and Babylonian priests compiled a standard series of 'astrological phenomena' in which the five schools of astronomers at Borsippa (near Babylon), Assur, Kalah, Niniveh, and Uruk added their comments and notes. By 600 B.C. this list of omens deduced from celestial phenomena comprised no less than 70 tablets with some 6500 to 7000 omina. This is the kind of astrology to which Isaiah refers (Isa. 47 : 13) when he forewarns Israel in these words: 'Let now the astrologers, the star-gazers, the monthly prognosticators, stand up and save thee from these things that shall come upon thee.'

This older form of astrology therefore was one of the different forms of divination; it had little or no influence on the development of astronomy and continued to be practised in classical and medieval days. The Etruscans and the Romans used similar practices to determine the *dies nefasti*, the unlucky days on which a general should not engage in battle or a certain undertaking should not be started. Drawing a horoscope or the 'art of genethlialogy' foretold the fate of an individual; it was not based on the observation of visible phenomena but on the invisible bonds which the planets and stars were said to have with this individual from the time of his birth onwards.

THE NEW ASTROLOGY

The new astrology required a method of calculating the relative position of the stars and planets at the hour of the individual's birth, which usually differed from that at the moment when he was consulted. He also had to refer these positions to the 'houses of the sun', twelve imaginary equal divisions of the sun's apparent path through the sky. Hence this form of astrology became possible only after the astronomers were able to calculate the paths of the planets through the sky and after they had agreed on dividing the ecliptic into the twelve houses of the zodiac. The oldest observational text mentioning zodiacal constellations dates

from the reign of King Nebuchadnezzar (568 B.C.), but they are not used as zodiacal 'houses' before a text of the fifth year of the reign of the Persian king Darius II (419 B.C.) in which astronomical computations are used for casting a horoscope. In the period between 600 and 400 B.C., that is in Late-Babylonian and Persian times, the zodiac as we know it was adopted by the astronomers, who were then also in the possession of the necessary mathematical tools to compute future and past planetary positions in the sky. Only in the sixth century B.C. were such conditions fulfilled as were needed for the rise of the new astrology. Hence the priests to whom Daniel refers (Dan. 5 : 7) as magicians, astrologers, Chaldaeans, and soothsayers lived in an age when the new astrology was born. It rose quickly to prominence, for we have ample evidence that a century later astrologers cast the horoscopes of prominent Greek citizens, and in the Seleucid period (300–0 B.C.) the number of tablets increased rapidly.

These centuries shortly before and after the destruction of the Assyrian–Babylonian empire and the rise of the Persian empire formed a prelude to Hellenistic civilization. Greeks were already visiting Mesopotamia and Persia and working for the local monarchs, Persian influences penetrated the western Semitic world, and the old Babylonian wisdom spread east and west. Ideas were exchanged and combined throughout the Near East.

Astrology is fundamentally of a religious nature, being based on religious tenets taken from different civilizations. It holds that the planets are of a divine nature. Both in Egypt and Mesopotamia each of the planets and stars had long been allotted to gods and spirits. It was also believed that these divine celestial bodies affected life on earth and could change the course of things. Hence invisible bonds joined the stars and planets with the living beings and inanimate things on earth; there was a harmony between the macrocosm of the heavens and the microcosm on earth. By studying the course of the planets and stars one could predict the future course of events on earth, for 'as it was above, so it was below'! This old Babylonian and Persian belief was reinforced by the doctrine from the holy books of the Persians,

the Avesta, which claimed that the soul of every living person comes down from a star at his birth and will return there after his death to await judgement. This principle of analogy between heaven and earth had already led the ancient Assyrians and Babylonians to assume relations between certain gods, stars, animals, plants, metals, and minerals. Several older texts illustrating this became more significant in this period. In the same way as we still speak of 'lunatics', the Babylonians believed that certain animals, plants, and stones belonged to a god and his planet, and this had a profound influence on medicine and alchemy.

The new astrology was not only born and propagated by the Mesopotamian schools of astronomers and astrologers, but also by the Persian Magoi, the 'servants of the gods', who like the Old Testament Levites formed an exclusive caste in Persian society, and travelled far to perform the religious rites and to explain the Avesta and its philosophy. The term Magoi was later used in an unfavourable sense, which still clings to the word 'magician'. The Greeks referred to the philosophers from the Persian Empire as Chaldaeans, whether they came from Mesopotamia or Persia, and whether they were philosophers or scientists.

HELLENISTIC AND ROMAN ASTROLOGY

Contact between the Chaldaean astrologers and the Greeks was established before the age of Plato, for we are told that a Syrian magus foretold the death of Socrates and that Euripides' lot was cast by a Chaldaean. The Greeks had used the celestial omens to forewarn farmers and sailors, but they had not practised this new astrology. Greeks like Democedes and Ktesias brought back some ideas about this new theory. Ktesias had known Eudoxus the astronomer, who was in contact with Plato about 367 B.C. Though Eudoxus rejected astrology and the possible influences of the planets on human life, by the time of Plato the divinity of the planets was generally accepted. In his *Republic* (x, 616) Plato mentions Babylonian astronomical beliefs, and in his *Timaios* (41 E and 42 B) he records the belief that 'every soul

belonged to a certain star'. This profound influence on Greek thought can be said to date from 260 B.C., when the Babylonian priest and astronomer Berosus founded a school on the island of Cos and wrote his *Babyloniaka*. The Greeks then became convinced that, as Diodor (II, 30) said, 'it is chiefly from the nature of these planets and the study of them that they know what is in store for mankind. And they (the Chaldaeans) have made predictions, not only to numerous kings . . . and in all their prophecies they are thought to have hit the truth. . . . Moreover they also foretell to men in private station what will befall them.'

Not all Greeks were convinced of the value of astrology. Carneades, the leader of the Platonic school (214–129 B.C., pointed out that the qualities and influences ascribed to the planets and signs of the zodiac were hypothetical and never proven. He also pointed out the varying fate of twins and asked why no horoscope was ever cast for animals! The Epicureans and some of the early supporters of the Stoa rejected astrology, which led to fatalism. However, penetrating the Near East in the wake of Alexander's armies, Greek civilization absorbed more Eastern tenets. Finally, Poseidonius the Syrian (135–51 B.C.) reconciled astrology with the Stoic principle of a divine spirit animating nature, and from his days onwards the Stoics were the strongest propagandists of astrology together with the Neo-Pythagoraeans and the Neo-Platonists.

During the amalgamation of Greek and Eastern tenets in the later Hellenistic and Roman era astrology was broadened by the absorption of new theories. By analogy to the divinity of the planets and stars, the signs of the zodiac came to be worshipped as supernatural. A solar theology, which recognizes the sun as 'the choir-leader of the planets', was gradually absorbed. The complete domination of man's fate by the stars, that is, astral fatalism, was more and more accepted. However, it was believed with the Pythagoraeans that by the study of the numbers prominent in the universe man can escape the fate read from the stars and become divine and immortal. In true Greek spirit the classical astrologers tried to lay down clear rules governing the influence

of the planets on earth, by means of their effluvia, on the *katarchai*, the circumstances which were more or less favourable for certain actions, on the calculation of the combined influence of a set of stars and planets, which by conjunctions, oppositions, and exaltations change each other's individual force; in fact on the causal relations between macro- and micro-cosmos.

Astrology reached Rome directly from the East, via Egypt, where it was already studied at the Academy of Alexandria. The earliest handbook, the lost *Astrologoumena*, is said to have been written by two Egyptians named Nechepso and Petosiris; others are ascribed to Manetho or to Hermes Trismegistos, who are also alleged to be the authors of alchemical works. Emperor Augustus made Marcus Manilius (*c.* A.D. 50) write the earliest Latin work on astrology, the *Astronomica.* A further long didactic poem by Vettius Valens (A.D. 150) and the *Mathesis* by Julius Firmicus Maternus (A.D. 335) also became very popular, in contrast with Ptolemy's more scientific handbook on astrology, the *Tetrabiblos* (A.D. 150), which was studied by the astrologers but not by the general public. Cicero's translation of Aratus of Soli's poem *Phaenomena* (275 B.C.) introduced the Romans to the ancient Greek art of forecasting from meteorological and celestial phenomena.

At Rome astrology found a ready reception, for its way had been prepared by the introduction of the solar calendar by Julius Caesar (46 B.C.), by the seven-day week, each day of which was dedicated to a planet, and by the official adoption of a solar theology during the Later Empire. It took firm root in the minds of many Romans and through them many astrological elements passed into the popular beliefs of German and other tribes beyond the pale of the Roman Empire even before other civilizing classical currents reached them.

The astrologers were called 'mathematicians' in Rome and several emperors tried to banish or forbid them to practise their art, which they probably feared rather than doubted. The early Christian church hotly combated astrological fatalism, which might lead to denial of ethical and moral values, but it never fully denied astral influences, though it held that man with God's help

could overcome the evil forces of the stars ruled by demons. This part-recognition of astrology helped to further the study of astronomy during darker centuries, for astrology, being applied astronomy, was helpless without proper astronomical background.

THE BIRTH OF ALCHEMY

The atmosphere which had given birth to astrology was also congenial to the rise of alchemy, the study of which is important because alchemy is the earliest phase of modern chemistry. The alchemist experimented, described, and classified his observations and tried to draw conclusions on the elements and their combinations in the various artificial and natural compounds. He discussed their reactions and changes but, because of the world in which he lived, his conclusions often took a philosophical or even religious form to which we no longer subscribe. Still, this alchemy was an honest attempt to understand the chemical properties of matter and as such we must honour these predecessors of the modern chemist and try to understand how their attitude changed to ours.

Pre-classical technology had amassed a host of observations on the animal, vegetable, and mineral world; it had classified them and used this knowledge to manufacture many products such as dyes, perfumes, cosmetics, fermented drinks, glazes, glass, alloys, etc. In these early technological and medical texts the hard-won empirical knowledge was often protected by the use of a secret or symbolical terminology, such as we later meet in alchemical texts. Thus castor oil became 'blood of a black snake' and copper 'eagle'. The profound knowledge of metallurgical operations had led to the discovery of the cupellation or 'fining' pot and the test for the purity of precious metals. However, the craze for these precious metals and stones had also prompted the craftsmen to imitate them and tablets giving recipes for 'synthetic' gold, silver, copper, or lapis lazuli have been found. Faked semi-precious stones were often prepared by 'boiling' minerals in chemical solutions or decoctions of certain plants.

It should also be remembered that pre-classical technology

often accompanied its operations with religious rites and prayers. The smith or the glass maker who smelted minerals to prepare new materials had to propitiate the spirits of the earth from which he tore his materials to hasten what he sometimes believed to be a natural process, such as the conversion of ores into metals or even that of one metal into another. His operations meant 'death' or 'resurrection' to certain materials and he recognized 'male' and 'female' forms of certain substances as did the later alchemist.

Greek atomistic and other theories on the structure of matter discussed in Chapter 4 impinged on such old beliefs. Those ancient Mesopotamians, who became curious to know the composition of matter, were not only deeply steeped in the ancient Mesopotamian religious and philosophical beliefs, but also in the new astral lore and had been in contact with the Magoi of Persia. The earliest chemical literature repeatedly refers to Zoroaster or his disciples as well as to Democritus and to mythical Egyptian sages like Hermes Trismegistus or even the god Toth as versed in alchemy and bent on teaching mankind this new science.

We have but few traces of this earliest incubation period of the new science, chemistry, in its home, Mesopotamia. The earliest types of reactions studied seem to have been those of metals embedded in powdered chemicals, in analogy to the carbonization of wrought-iron by charcoal or the formation of brass from copper heated in powdered zinc ore. In the early chemical writings such processes are contrasted with the 'Egyptian methods' of exposing a metal or compound to the vapours of certain substances. For the new alchemy was soon studied at the Academy of Alexandria, the Museion, and in fact the earliest author so far known was a Graeco-Egyptian called Bolos Democritos of Mendes, who lived about 200 B.C. and who was one of the earliest leaders of the Neo-Pythagorean school of philosophy. His *Physika* (*Nature's Secrets*) consists of four books on the 'making' of gold, silver, gems, and purple, and its data have been culled from Egyptian, Jewish, Babylonian, and Persian sources. Ostanes the Magus is here mentioned as the teacher of Democritos in the field of chemistry.

ALEXANDRINIAN CHEMISTRY

When Bolos first codified chemistry the basic Mesopotamian, Greek, and other constituents were already strongly fused. The four-elements theory of the Greeks was applied in a particular way. Aristotle and others had stressed the importance of the 'qualities' of the elements air, water, earth, and fire rather than the elements themselves. Writings of Plato and other philosophers contain passages referring to a primary matter, which is neutral and turns into a specific element by absorbing its 'quality' (or characteristics) in the same way as the odourless substratum of the balsam-cookers absorbs the heavily scented essential oil. In the hands of Bolos and other members of the Hermetic and Stoic schools the 'qualities' of Aristotle's theory become more and more materialistic characteristics to be added to or subtracted from the neutral sub-stratum. By chemical reactions it is possible to separate the 'essence' or 'spiritus' from an element or substance and to transfer it to another. The alchemist thus seeks to obtain the 'spirits' of his chemical compounds in order to be able to change them at will and to perform a 'transmutation' of such substances as gems or metals.

Bolos gives excerpts from recipe books of dyers, several of which seem to have existed in this period; one of them, dating from the seventh century A.D., is in the Berlin Museum. However, Bolos was not interested in the recipes for dyeing as such but only in the changes in colour, which to him and his fellow-alchemists seemed to indicate an essential change in the coloured body due to a chemical reaction. To them the colouring of their chemical indicated that actual 'transmutation' had taken place and hence they studied such colourings and used the technical terms of the dyers to denote such changes of matter as they believed to observe. In primitive chemistry the 'transmutation' of compounds such as metals began by reducing ('corrupting') the primary material to a neutral 'earth', which was prepared for the implantation of such amounts of 'water' (fusibility), 'air' (brilliancy), and 'fire' as was needed. Hence the reactions began

by a 'blackening' (fusion with sulphur or the like), followed by a 'whitening', a 'yellowing', and finally the 'iosis' (imparting a purple colour), would turn it into definite gold.

In the hand of these alchemists the essential individual qualities which built up the Aristotelian 'form' of every substance became subtle fluids called 'pneuma' (breath) or 'spiritus'. They could be prepared from any substance by prolonged heating or repeated distillations. Hence the Alexandrinian alchemists developed new chemical techniques, borrowing much apparatus from the kitchen and from the chemical technologists to distil, boil, and heat their substances in alembics, closed vessels, digesters, and pots to recover this 'spirit' or to 'project' it onto the substance to be changed, which was placed in the top of the vessel to be 'transmuted' by the rising vapours of 'sulphur', 'arsenic', and 'mercury', or rather of compounds containing these elements.

This method of 'projecting' the reagent on to the substance to be changed is typical of the Alexandrinian alchemists, who excelled in devising new apparatus for their research into the nature of matter. After Bolos's *Nature's Secrets* we have to wait some two centuries before we find Anaxilaos of Larissa (*c.* 50 B.C.) writing a *Baphika* (*Colouring*) on the changes which take place when the colours of substances change. Then in the first centuries of our era we find many more chemists. In fact we can distinguish a practical school (Isis, Jamblichos, Moses, Ostanes) and a philosophical school (Maria the Jewess, Comarius, Hermes, Cleopatra) of authors who take mythical names to enhance the value of their treatises. The writings of Bolos and Anaxilaos are only known through fragments, which can be found in the so-called Leiden and Stockholm papyri discovered in a grave at Thebes (Egypt) together with several magical papyri, which collection seems to have belonged to an early alchemist. Parts of these papyri have been culled from a dyer's book of practical recipes. This codification period of early alchemy ends with Zosimos, who about A.D. 300 summarized the whole of alchemical doctrines and literature. His writings already showed a strong religious bent, as he holds that salvation can be obtained by the Great Work of the complete transmutation of metals.

THE NEW ALCHEMISTS

In fact we can distinguish four trends in chemistry from the days of Bolos onwards. There were the chemical technologists, who conducted their trade or 'mystery' of producing useful chemical products, mostly carefully guarding their trade secrets, or writing recipe books which do not disclose all phases of their trade, or are partly couched in secret language. Such recipe books continued to be collated until the days of Lavoisier.

Secondly there were the true practical alchemists, who believed in the possibility of transforming any kind of matter into another. By inventing all kinds of apparatus and operations to conduct such 'colourings' and 'loosenings of the pneuma' they contributed much to the evolution of laboratory techniques and to the discovery of useful chemicals. As late as A.D. 484 Aeneas Baraeus, a Greek theologian of Gaza (Syria), informs us that such alchemists formed a recognized group of artisans with a certain standing and a lore of practical procedures.

After the days of Zosimos a third group of chemists gained in importance. They were mainly Neo-Platonists or Gnostics to whom alchemy was part of their religio–philosophical doctrine. Such alchemists as Stephanos and his school (eighth century A.D.) were no longer interested in the transformations of matter as such, as was the small fourth group of theoretical alchemists, the true precursors of the modern chemist. The 'Hermetic Philosophers' like Stephanos use the chemical knowledge gained in the laboratory as symbols. Thus the transmutation of the metals stands for the regenerating force of religion in transforming the human soul. Their interest lies in the religious sphere; they mix alchemical texts with prayers, invocations, moralizing paragraphs, and allegories. Chemical operations are interpreted in their allegorical-symbolic language. Others accompanied alchemical operations with music to achieve the proper harmony between body, soul, and the music of the spheres.

By the time of Stephanos, when alchemy was mainly studied in Syria and some of the writings were in Aramaic or Syriac instead

of Greek, the Hermetic Philosophers had largely submerged the theoretical alchemists and turned alchemy to the salvation of the soul. But Stephanos's experimental attitude was not completely lost; it was revived by Arab alchemists. The Byzantine alchemists like Michael Psellos knew their Bolos Democritos and their Zosimos, but they had little to add to this store of knowledge: they confine themselves to theoretical speculations on known data and experimental alchemy seems to have languished in Byzantium.

ARAB ALCHEMY

Alchemy had found few adherents in the West; its evolution was centred in the eastern part of the Roman Empire. Hence there were no direct links with alchemy in western Europe and alchemy came to be known only during the twelfth century, when treatises on this subject were translated from Arabic versions along with astrological essays.

The earlier Alexandrian treatises were transmitted partly by the Byzantine alchemists, partly by the Arabs, who soon after the conquest of the southern coasts of the Mediterranean showed great interest in every phase of Hellenistic culture. Alchemical literature was translated from the original Greek or Syriac into Arabic and studied closely. In Arabic alchemy too we find the speculative Hermetic philosophers side by side with practical alchemists like Jâbir ibn Hayyân (ninth century), who held that the specific properties of chemicals are measurable as they are built up according to mensurable relations, thus sowing the seed of quantitative chemistry.

Arab alchemists also introduced Chinese and Indian concepts into Greek alchemy. They modified the transmutation theory, as they believed with Aristotle that the metals and minerals in the earth had been formed by 'moist' and 'dry' vapours. Out of the many 'spirits' or volatile bodies then known sulphur and mercury seemed to them to embody these qualities to perfection. The plasticity and fusibility of metals were caused by 'mercury', the combustibility and oxidation ('rusting') by 'sulphur'. Hence gold

was held to be rich in 'mercury' and poor in 'sulphur', the latter being preponderant in iron or any other base metal. Their transmutation could be effected by a powder to be sprinkled on the metal (Greek *xerion*) or by a 'medicine' (Greek *pharmakon*) to be added. This they expressed in the Arabic term *al-iksîr* (our 'elixir'), the preparation of which started with cinnabar, the red compound of sulphur and mercury.

This idea of a 'powder of projection' seems to go back to China. We have little evidence on early Chinese alchemy, which seems to have arisen independently in the third century B.C. Chinese philosophy already speculated on the Two Contraries, *Yang*, the male, active, fiery principle, and *Yin*, the female, negative, earthy, and dry principle. It also discussed a system of Five Elements (*Wu-hsing* – water, fire, wood, metal, earth). The aim of this Chinese alchemy seems to have been the preparation of a substance which ensured longevity. Gold was only used to shape vessels from which potions of longevity were drunk or for the manufacture of the 'pill of immortality' in the preparation of which cinnabar, having the colour of blood and mercury, 'the living metal', played its part.

Adopting such ideas the Arabs made their contribution by looking for the 'alkahest' or 'universal solvent' which would dissolve the organisms or salts causing diseases in living bodies and imperfections in minerals and natural substances. These Arabic Hermetic Philosophers were constantly criticized by more rational Arab alchemists like Jâbir and Râzî, who tried to analyse the properties of air, water, fire, and earth and the deficiencies or excesses of these elements in other chemical substances. They developed a formidable body of real chemical knowledge and practical techniques which came to the West by way of Byzantium, Italy, and Spain.

MEDIEVAL ALCHEMY

In 1144 Robert of Chester translated the first alchemical book into Latin. In rapid succession more alchemical treatises revealed the Hellenistic–Arabic–Chinese alchemical doctrines and the West

was soon deeply interested in the Elixir, the Philosopher's Stone, the Alkahest, 'Palingenesis' or the resurrection of plants out of their ashes, the 'Fountain of Youth' and the 'Quintessence' (pneuma), 'Potable Gold' and the 'Universal Medicine'.

Even if based on wrong hypotheses, active experimentation soon led to important discoveries such as the manufacture of alcohol (twelfth century A.D.) and sulphuric and nitric acids (thirteenth century A.D.). This widened the scope of both alchemists and chemical technologists (pharmacists), for it enabled them to extract many natural products and minerals and to study reactions in solutions. Formerly their method of distillation without condensation of the distillate at low temperatures had prevented them from producing low-boiling products such as alcohol. It had also led to the overheating of chemicals in their stills and to the cracking of the distillates, limiting their experiments to reactions in the molten or liquid state. Now they could prepare solutions and decoctions and study the reactions of the active compounds of natural substances more closely. Western alchemists like Raymond Lull (1232–1316) also took over earlier attempts to use certain symbols for chemicals and chemical operations, though they were still hampered by the fact that they worked with natural impure substances which made identification and repetition of experiments very difficult.

Research on the acids and alcohol continued, prompted by the zeal to isolate the most active principle, the quintessence. Hence much attention was focused on the preparation of alcohol, a powerful solvent for natural substances and a most useful tool in the hands of the pharmacists who, being unable to extract and concentrate the active principles, had until then merely collected and sold natural substances. The redistillation of the impure 60 per cent *aqua ardens* (burning water) yielded the much stronger *aqua vitae* (water of life). In the fourteenth century redistillation with quicklime yielded 100 per cent alcohol. Its restorative, preservative, and extractive qualities were widely studied and turned to practical use.

Many medieval alchemists turned from theoretical speculation to the preparation of useful products and wrote voluminous

compendia embodying their practical experiments and recipes. These pharmacists and distillers prepared alcoholic extracts and distillates and manufactured medicines. In 1463 the first public dispute on the correct way of preparing the quintessence was held at Padua, followed by others at Padua and Siena in 1512. This movement not only started pharmaceutical chemistry on its course; it also caused after the introduction of printing a flood of 'distillation books'.

The Church did not combat this practical and theoretical alchemy. Albertus Magnus (1193–1280) and Thomas Aquinas (1224/5–74) were allowed to study 'the transmutation of the metals, that is to say the imperfect ones, in a true manner and not fraudulently'. It only condemned the practices of quacks and 'puffers' who practised alchemy together with astrology and other occult sciences, using astrological signs to denote its operations and calculating astrological influences promoting the 'Great Work'. The Papal Bull *Super illus specula* (1326) and similar pronouncements only banned the alchemical charlatans, not the true seekers of chemical truths.

MEDIEVAL ASTROLOGY

Astrology was strongly embedded in the culture of the Roman Empire and the popular books on astrology were inherited by the West. There was no break of several centuries in this tradition as there was with alchemy. Though Ptolemy's handbook on astrology, his *Tetrabiblos*, was not known completely until much later, the early Middle Ages knew Macrobius's commentary on Cicero's *Somnium Scipionis* (*Dream of Scipio*), which goes back to the fifth century A.D., and some of the Roman handbooks already mentioned, and by the twelfth century many such handbooks were translated from the Arabic or Hebrew in Spain and Sicily.

There was no doubt that the Church did not officially tolerate forecasting the future of individuals from the stars. The fatalistic beliefs that man's actions were fully determined by the stars and planets conflicted with the dogma of free will. On the other hand Aristotle, who with Augustine dominated early medieval thought,

had on several occasions admitted the possibility of astral influences in daily life. It was believed that physical forces emanated from the planets and stars to act upon earth; such forces could have their effect on the human body and in this way on the human soul. However, it was held with Ptolemy that mankind, having been forewarned of such influences, could escape this fate by acting upon such signs.

Medieval theology therefore, while tolerating certain aspects of astrology, banned others. We must not forget that it was still generally accepted that the celestial bodies were propelled by supernatural intelligences; they were not yet believed to consist of the same chemical elements and compounds as the earth and they were never discussed as material spheres revolving in the universe. Hence it was thought that they exerted physical forces which might influence diseases or other defects of the human body, and 'medical astrology' was tolerated and even taught by churchmen. Other forms of astrology were also widely adhered to. Thus we find systems of '*electiones*', giving rules to determine the correct dates for undertaking journeys or transactions, and '*interrogationes*', rules to find lost or stolen property by means of the stars. In short such ancient superstitions as are still printed in certain magazines and daily newspapers were rampant in the Middle Ages.

The church authorities did, however, combat with all their force any use of astrology which might lead to fatalism. When prominent thinkers like Albertus Magnus, Thomas Aquinas, and Robert Grosseteste (*c.* 1175–1253) discussed astrology they did not deny astral influences on daily life or the possibility of reading a man's future from the stars. But they held that, being forewarned, one can of one's own free will avoid the dangers which lurk in the stars and they considered it sinful to prophesy from the stars what the future holds in store for our actions.

This rather ambiguous attitude towards astrology had strange consequences. Thus the Franciscan Bartholomeus Anglicus could write his popular encyclopedia *De proprietatibus rerum* which explained how everything on earth was submitted to astral influences. This very popular work, which was repeatedly

reprinted in the fifteenth century, gives lengthy quotations from Arabic authors to prove details of astrology and the author did not even deem it necessary to warn the reader against the fatalism inherent in astrology.

Roger Bacon (*c.* 1210–*c.* 1293) even held with the Arabic astrologer Albumasar that the birth of a new religion took place under a specific conjunction of the planets. Thus Christianity was born under the conjunction of the planets Mercury and Jupiter, Islam under that of Venus and Jupiter. Others, such as Siger of Brabant, led by the Stoic theory of a periodically recurring cycle of events, of a recurring birth and passing away for instance of our universe, even maintained that Christianity had existed and perished many times. Such theories were, of course, abhorrent to more orthodox Christians and such speculations may well have been one of the reasons why Roger Bacon was imprisoned and sentenced.

Astrology was doomed with the advent of the new astronomy, but during the Middle Ages it helped to multiply the number of astronomical observations and to improve the instruments of the astronomers, for which reasons it deserves its place in the history of science.

CHAPTER 6

Science in the Early Middle Ages

THE DECLINE OF GREEK SCIENCE

AT present we are inclined to consider it as normal that, once a science has started to develop, it steadily continues to do so. Each subsequent generation of investigators commence their work at a higher level than those preceding them, because they can go on where their predecessors left off. And evidently there is never any lack of new fields of investigation to be explored.

But the situation is not necessarily so simple as this. In classical Hellas at least it took a different course. After reaching a certain standard science came to a standstill and even declined. There is, for example, not a single indication that ancient astronomy ever proceeded beyond the stage reached by Ptolemy in the second century A.D.; there is no evidence of any progress in theoretical mechanics and hydrostatics in comparison with what had been attained by Archimedes in the third century B.C., nor is anything known of any further development in mechanics after Heron. The third century A.D. admittedly produced a few great mathematicians such as Pappus and Diophantus, but there are reasons to assume that these were isolated phenomena which were not representative of any appreciable increase of mathematical knowledge. Moreover, the achievements of the great mathematicians of the past, such as Archimedes and Apollonius, may be regarded as having fallen into oblivion rather than as providing starting points for new investigations.

We shall not enter into the question whether these trends may possibly be understood in connexion with the general political and cultural history of Greece. We shall only draw attention to a circumstance which certainly contributed to them: the absence of systematic intensive education of the broad masses of the people in the fundamentals of mathematical and natural science,

as is common in present-day society and which continually imparts new impulses for studying these subjects.

If for the reasons stated above the development of natural science in Greece was not an uninterrupted growth, still less was it so in other countries, even those where science was eventually to flourish most. In the first centuries of the Christian Era there was not a people in the world that had reached a sufficiently high intellectual level to keep burning and to stimulate the fire that had become nearly extinct in Hellas. Science was therefore at one time threatened with the danger that it would no longer find shelter in the country of its origin, while other countries were not yet prepared to receive it.

This danger was averted, as can be established in the light of after events. Science found a new home in Western Europe, where the development that had become stagnant in Greece was continued. It is a question of great importance for cultural history how Greek science reached this new home and what happened to it there. It is at any rate certain that, although there were interruptions as regards place and time, there was none in respect of substance. No new science was founded here on new bases, but use was made of the foundations that had been laid in Hellas.

Before entering into this question it may be well to realize that with the introduction of Christianity a new factor had made its appearance in history with which the development of natural science proved to be closely related. The relationship between natural science and Christianity constitutes a chapter of the history of civilization that is as interesting as it is complicated, and which has never been treated sufficiently deeply or to an adequate extent and seldom with complete understanding of all its various facets. We shall, of course, have to confine ourselves to a few general considerations.

Generally speaking it may be said that during the first centuries of its existence Christianity was not conducive to scientific pursuits. Science was regarded with suspicion because of its pagan origin; moreover, the ideal prevailed that it was not advisable for the spiritual welfare of Christians to penetrate more

deeply into the secrets of nature than was made possible by the Holy Scriptures and than was required to understand these.

This point of view, however, could not possibly be maintained permanently. The thought presented itself that it should certainly be regarded as a duty for a believer in a Creator of heaven and earth to become acquainted with the work of His hands. In addition, the interpretation of the Bible, in particular of the account of creation in Genesis, at once raised questions of a scientific nature. Various patristic authors accordingly display an attitude towards natural science which can certainly not be regarded as essentially repudiatory. They all agree, however, that science should always remain subservient to the authority of Holy Writ, which far surpasses any capacity of the human mind. The principle thus laid down imposed upon scientific investigation a restriction of which due account had to be taken and which gave rise to numerous difficulties.

Despite the hostile attitude towards heathen thought often adopted by Christian authors at the time when Christianity still had to fight for its existence, Greek doctrines exercised a great influence. During the first centuries this was in particular the case with Plato's philosophy, a close relation being found between the description in his dialogue *Timaeus* of the building of the world by a good Demiurg and the account of creation in Genesis. The transcendence of Plato's world of ideas harmonized with the Christian conception of God and the ideas themselves could without restraint be interpreted as being thoughts of God. The close relationship thus established between Christianity and Platonism was to be maintained throughout the period when St Augustine's (354–430) theology was the predominant school of Christian thought, that is, until the beginning of the thirteenth century. Another great influence, especially in the early Christian era, was that of Neo-Platonism, the doctrine on which various patristic authors had been reared. In view of our observations (p. 41) on the low appreciation of matter which is characteristic of this philosophy it will be clear that its influence was not beneficial to science.

HOW GREEK SCIENCE PENETRATED WESTERN CULTURE

Proceeding to the consideration of the paths along which Greek thought on nature penetrated into Western Europe we can distinguish three areas of culture which contributed to the preservation of Greek science and helped to spread it. They are Rome, Byzantium, and Islam. Their contributions were different and by no means of equal importance, but none of them should be omitted from a history of natural science.

ROME. However immense Rome's importance for the world has been and however gifted the Roman people were in many respects, they obviously had no aptitude for the practice of mathematics and natural science. Not a single contribution could be mentioned with which they enriched either. However, when they conquered Greece and came into contact with Greek culture, there followed the well-known phenomenon of the more highly cultured conquered people being the mental conqueror of the conqueror. Greek thought became an ideal to be striven after by the intellectual Roman, and a stay in Greece was regarded as indispensable to education.

Evidence of this mental attitude is provided by the typical Roman tendency to compile encyclopedias comprising and preserving as much as possible of Greek knowledge. These compilations have generally no scientific importance, but they did much towards preserving and transmitting culture. In the field of natural science special mention should be made of Pliny the Elder's (A.D. 23–79) *Naturalis historia* and Lucius Annaeus Seneca's (4 B.C.–A.D. 65) *Naturales questiones*, which formed a direct or indirect source of the early medieval knowledge of ancient science.

The Roman scholars Boethius (*c.* 480–524) and Cassiodorus (*c.* 490–*c.* 580) may possibly have exerted an even greater influence shortly before the definite collapse of the West Roman culture. Through the ages Boethius has remained known for his work *De consolatione philosophiae* (*On the Consolation of Philosophy*), his epithets 'the last Roman and first Scholastic' and

'teacher of the early Middle Ages' briefly characterizing his historical position. Although he failed to realize his ambitious plan to supply a Latin translation of all the works of Plato and Aristotle, Western Europe became acquainted with important elements of Greek science through his publication of some of Aristotle's writings on logic and of works on arithmetic, geometry, astronomy, and music. Cassiodorus established in the monastery Vivarium which he had founded the tradition of scientific study by monks. He argued that the study of Holy Writ requires as preparation the practice of profane science. In his work *De artibus et disciplinis liberalium literarum* he introduced the division into *artes* (grammar, rhetoric, dialectic) and *disciplinae* (arithmetic, geometry, astronomy, music) as subjects to be studied for this purpose, and this division continued under the terms *trivium* and *quadrivium*.

We mention a few other Latin works which were instrumental in handing down Greek views to the Middle Ages:

(i) A translation of part of Plato's *Timaeus* with a commentary by Chalcidius (first half of fourth century);

(ii) A commentary on Marcus Tullius Cicero's (106–43 B.C.) *Somnium Scipionis* (*The Dream of Scipio*) by Ambrosius Theodosius Macrobius (*c.* 400);

(iii) The encyclopedia *De nuptiis Philologiae et Mercurii* (*On the Marriage of Philology and Mercury*) by Martianus Minnaeus Felix Capella (second half of the fifth century A.D.).

BYZANTIUM. The eastern part of the Roman Empire never knew the deep cultural degradation to which the western part succumbed. Constantinople was a centre of Greek science and remained so until it was conquered by the Turks in 1453.

Byzantium scholars were upon the whole more conservative than creative. At one time, however, they were of great importance at least for mathematics. In the beginning of the sixth century the mathematician Eutocius wrote commentaries on works by the two Greek mathematicians Archimedes and Apollonius, who were already sinking into oblivion. It seems that he knew no other works by Archimedes than the three (*On the Sphere and the Cylinder*, *Measurement of the Circle*, *On the*

Equilibrium of Planes) upon which he commented. If he had not preserved the Greek text of Books I–IV of Apollonius's *Concia* we should probably not know them in their original version any more than we do the later books of this work. In the same period Anthemios of Tralles and Isidoros of Miletus, architects of Sancta Sophia, seem to have founded in Byzantium a school in which Greek mathematics was studied, even if it was not further developed. It is also owing to the activity of Byzantine scholars that the works of Archimedes were eventually almost completely collected there. The codex containing them as well as manuscripts of works on mechanics and optics ultimately found their way to the centre of culture founded by Norman princes and their successors of the Hohenstaufen family in Sicily and southern Italy, from where eventually they came to Western Europe.

ISLAM. Neither of the two means of transmission described above can compare in importance with the third, that of Islamic culture. The tremendous energy which propelled the political expansion of the Arabs from the seventh century onward was attended with a remarkable capacity to assimilate what the older and richer civilizations of the subjected countries had to offer.

Contact with Greek science was chiefly established in the Near East, where extending Christianity had brought Hellenic and Hellenistic culture. The sects of the Nestorians and Monophysites which had been banished from Constantinople had founded schools there in which theological education had naturally led to the study of Greek philosophy. For the benefit of students Greek texts of a philosophical nature and presently also on various branches of science had been turned into Syrian. Finally the University of Jundī-Shāpūr, where pagan philosophers who had been driven from Athens by the emperor Justinian (483–565), for example Simplicius (first half sixth century), the commentator of Aristotle, and the Neo-Platonist Damascius (*c.* 458–533), had also taken refuge, had become a nursery of Greek culture, and, mainly in the eight and ninth centuries, became a centre of assimilation of this culture by Islam. This assimilation was greatly furthered because al-Mansūr (*d.* 775), Hārūn-al-Raschīd (*c.* 765–809), and al-Ma'mūm (786–839), the great caliphs of the

House of the Abassides, vigorously stimulated the translation of Greek works into Arabic. These translations were at first often made via Syrian, but already under al-Ma'mūm there was at Baghdad a complete translation institute where, under the direction of Hunain ibn Ishāq (809–77), numerous direct translations were made from Greek into Arabic. Interest was at first mainly focused on medical and astrological works, but soon it was also directed to astronomical, mathematical, and philosophical writings and it may safely be said that, when the ninth century was drawing to its close, an appreciable portion of the principal remains of Greek philosophical and technical literature was accessible in Arabic.

Greek culture was not the only source for Islam to draw upon. It was also enriched by borrowings from what the Hindu's had achieved, notably in the field of mathematics. This source supplied two acquisitions which have been so completely absorbed in present-day science that anyone who is not sufficiently historically minded finds it difficult to realize that they were extremely important discoveries and is therefore inclined to undervalue them. They are: the place system for writing integers, which enables them all to be represented by means of the ten symbols 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9 (comparison with the Greek and Roman systems of figures shows the immense progress thus achieved); and secondly, the introduction of the sine as a measure of an arc instead of the chord used by the Greeks for this purpose.

If Islam had done no more than assimilating and preserving Greek and Indian lore, its historical significance for the development of natural science would already be greater than that of Rome and Byzantium together. It surpasses them even more because many Islamitic scholars also enriched science by independent discoveries. It would be beyond the scope of the present work to enter deeply into this; moreover, the merit of their achievements was too often in the sphere of pure mathematics to justify treatment here. It will suffice to mention the names of only two scholars out of a large group who contributed to the growth of science:

The astronomer al-Battānī (Latin Albategnius, *c.* 858–929),

author of an important textbook on astronomy which had great authority up to the sixteenth century. By accurate observations he improved various astronomical constants (e.g. the constant of precession) and discovered the progressive motion of the line of apsides of the sun's orbit, which had not been noticed by Ptolemy. He also brought goniometry to a higher degree of development.

The mathematician, physicist, and astronomer ibn-al-Haitham (Latin Alhazen, *c.* 965–*c.* 1039), whose historical significance is mainly based on his great work on optics, *Kitāb al-Manāzir*, which under the title of *Opticae Thesaurus* occupied an important place in European physics down to the seventeenth century. He gave a better (though not quite correct) description of the structure and operation of the eye. His name remained attached to the problem of how to determine a point on a convex spheric mirror on which a light ray from a source of light will be reflected in such a way that the ray will reach the eye of a given observer. He also discussed the phenomena of twilight which he wanted to use to determine the height of the atmosphere. Other names of Arabic authors will be mentioned in retrospect when the occasion arises.

A counterpart of the way in which Islam had mastered the results of Greek thought is the eagerness with which in the twelfth and thirteenth centuries Latin Christianity absorbed the treasures of wisdom and knowledge available from Arabic sources. An important point of contact was the Kingdom of the two Sicilies, referred to above in connexion with Byzantium. Arabian influences had already penetrated there in the eighth century during Saracen domination. But Spain, where Cordoba and Granada were strongholds of Islamic culture, became of even greater importance. The principal centre of transmission was Toledo, which after the conquest by the Christians in 1085 had remained the seat of Eastern science. A school of translators was formed here whose work was to become of the greatest importance for west-European science.

Whereas Syrian had formerly been the link between Greek and Arabic, Arabic now formed the connexion between Greek and

Latin until here, too, direct translation was possible. In addition to the Toledan translators others were working elsewhere, one of whom, Gerard of Cremona (1114–87), has ninety-two translations from Arabic into Latin to his name.

THE BEGINNINGS OF EUROPEAN SCIENCE

The influx of science and philosophy pouring into Western Europe via Arabic or in direct translations irrigated a soil which had meanwhile been producing its own fruit. It was not luxuriant, but the work of those who in the Dark Ages after the fall of the West Roman Empire had kept the flame of culture burning, however feebly, deserve the gratitude of posterity.

About 600, the Spanish Bishop St Isidore of Seville prepared the encyclopedic works *De natura rerum* and *Origines*, which incorporated complaitory works of Roman authors as well as Patristic writings. Using these encyclopedias in addition to Pliny's *Naturalis historia*, which was unknown to St Isidore, the English monk Bede (Baeda Venerabilis) wrote early in the eighth century a work *De natura rerum*, which was to become an important source of the knowledge of nature in subsequent centuries. His activity (which was also important for mathematics, chronology, and computi, e.g. the calculation of the calendar) forms part of the tradition already prevalent in early times in Irish and English monasteries (Clonard, Bangor, Iona, Wearmouth, Jarrow) of not neglecting the study of profane science by the side of theology. Profane science was also practised at St Peter's school at Canterbury and the episcopal school at York.

Alcuin, a pupil and later a teacher at this school, was called to France in 780 by Charlemagne to cooperate in the endeavour to raise culture, which is usually referred to as the Carolingian Renaissance.

Similar work was done in Germany by Alcuin's pupil Hrabanus Maurus (776–856), of a monastery at Fulda and afterwards Archbishop of Mainz, who was accorded the honorary title of *Primus Germaniae praeceptor* because of his extensive work in the encyclopedic and didactic sphere.

About the year 1000 we find in France the remarkable figure of Gerbert of Aurillac, later Pope Sylvester III, who profited from a stay in Spain to acquire knowledge from Eastern sources. He practised mathematics and astronomy independently and, both by his activity at the school of Rheims and by his later influence as an archbishop and a pope, contributed to raising the intellectual level of the clergy, who at that time were the exclusive students of science.

The spirit created by him, to be described as a study of ancient culture with a strong mathematical and scientific trend, survived in the cathedral school of Chartres, which flourished greatly under the direction of his pupil Fulbert.

This school had its heyday in the twelfth century under the leadership of Bernard of Chartres and afterwards of his brother Thierry. It was then a centre of intellectual life with which almost all authors of that time who are of importance for the history of natural science were connected in one way or another, such as:

Adelard of Bath, an English scholar who in the first years of the twelfth century travelled about France, southern Italy, and the Near East; author of two works of a philosophical and physical nature, *De eodem et diverso* and *Questiones naturales*, in which the influence of Arabian science is manifest, and translator of Arabic writings into Latin. He also has to his credit the oldest Latin translation of Euclid's *Elements*.

William of Conches (1080–1145), author of a commentary on Plato's *Timaeus* and of a *Philosophica mundi*, which owing to its corpuscular considerations evoked theological opposition. Anything savouring of Atomism inevitably aroused suspicion in the Middle Ages because it always suggested Epicureanism and thus heresy.

On the eve of the breakthrough of Aristotelianism, to be discussed in the next chapter, the period in which Platonism reigned supreme in scientific thought was to some extent terminated by the work of Alanus de Insulis (*c.* 1128–1202). He is of special importance for our subject because of his use of the concept Nature. This is a creature of God, which at His command and in His place tends and guides the development of the material

world; it is the all-governing, law-giving, and formative power behind events.

There was a great future for this conception which, like so many conceptions prevailing in the twelfth century, originated in Plato's *Timaeus*. The hypostasis Nature was at all times turned to excellent account, if not in the strict study of natural science, at any rate in less exact common parlance: Nature permits or forbids things; it shows preference or abhorrence; people can act in harmony with Nature or infringe its laws, etc. Inevitably, if the Creator left the guidance of the material world entirely to Nature, it was bound to become the object of veneration in His place.

AN EVALUATION OF EARLY MEDIEVAL SCIENCE

It is interesting to the historian of natural science to peruse the works of the above-mentioned authors and numerous others of the same period. The modern reader who comes into contact with them without historical preparation will, however, generally be inclined to attach little value to them, because they are too far removed from what he has learned to understand by natural science. He cannot all of a sudden eliminate the scientific training he has received; therefore he only sees the shortcomings and gives too little thought to the great difficulties that had to be overcome to attain the high degree of development science has now reached.

At the time with which we are now dealing these difficulties were threefold, arising from:

(i) The general attitude of mind of the scholars;

(ii) The low level of mathematics;

(iii) The essence of natural science.

A few remarks will be made on each of these.

(i) The reader should begin by entering into the feeling of awe of the authority of tradition in which medieval philosophers had been brought up, and bear in mind that this feeling dominated the sphere of natural knowledge as rigorously as that of faith. As regards faith, the authority of the Church was accepted without

criticism, and in respect of natural knowledge there was hardly less confidence in the authority of Greek authors who had as it were been sanctioned by it. This naturally led to the assumption that, just as the Revelation has been laid down once and for all in Holy Writ and the commentaries of the Fathers, likewise the essence of natural knowledge had been definitely established in the works of the great scientific writers of Antiquity. Natural science was not regarded as something that has continually to be freshly acquired and which requires steady and continued study; people were convinced that it already existed, at least that it had once existed and that the question was how to retrieve it. Nobody should be misguided by the numerous pronouncements by medieval authors which, often couched in strong words, refute any conclusive power of an appeal to authority in worldly matters. The authority with which Greek philosophers were endowed was an intrinsic authority, and the same authors who so emphatically reject an appeal to this authority as an argument are so greatly influenced by their philosophy that they adopt the essential features of their picture of the physical world with as little criticism as the devoutest follower would have done; they submit to what they regard as the authority of truth.

(ii) The second cause impeding the coming into being of an independent medieval natural science, and which would have impeded it just as much if people could have had a clean start and had not felt tied down to what the Greeks had already done in this field, was the very low level of mathematics. This prevented the inception of any quantitative physical theory, and in general deprived natural science of the means of expression which afterwards proved to be an essential requirement. It has occasionally been surmised that it was also or even chiefly a deficiency in technical development that obviated the growth of physics. It seems improbable that this factor was of any significance. The technical development at a time which produced big cathedrals with stained-glass windows would certainly have been able to procure the simple instruments required by physics for its initial development in an experimental direction if there had been a need for them.

(iii) But there was no need for them because – and here we touch upon the third cause and at the same time upon the root of the matter – there was no clear conception of how natural science had to be practised in order to attain its dual purpose: the acquisition of insight into natural processes and the control of the natural forces thus revealed. This conception had to be acquired by experience; also in this respect natural science is empirical in nature. The Greeks seem to have realized spontaneously how mathematics was to be studied and all other peoples learned it from them. They did not, however, know the truly efficient method of studying natural science and centuries were to elapse before this was gradually found out. This method may seem evident to people of modern times; as a matter of fact the intricate combination of experience gained either unintentionally or by conscious experimenting, hypothesizing, and experimentally verifying deductions drawn from this is by no means simple and obvious. It is one of the important results of the history of natural science that it has taught us this and thus made us appreciate the value of scientific method.

We cannot conclude the discussion of the period dealt with in this chapter without drawing attention to the fact that towards its close there were the first manifestations of a power which was to acquire great importance for the further history of European culture: the university, which was to become the third power by the side of Sacerdotium and Imperium, Priesthood and Empire (later Church and State). Although this new power did not come into its own until the thirteenth century and later, the twelfth century had already given birth to the two universities which were to govern and influence most strongly the medieval study of science: those of Oxford and Paris. Their special importance for the development of natural science will be examined in greater detail in the next chapter.

CHAPTER 7

Science in the Later Middle Ages

THE RISE OF ARISTOTELIANISM

IN addition to the foundation of universities, which was mentioned at the end of the preceding chapter, around the turn of the twelfth century there were two other influences of no less importance for the development of culture: the spread of the knowledge of Aristotle's works and the foundation of two orders of mendicant friars, that of the Dominicans (1216) and that of the Franciscans (1223).

Aristotle had been known previously, but exclusively as a logician and not even completely as such. Now, however, all his works, in particular his *Metaphysica*, *Physica*, and *De caelo*, became available through translations, at first via Arabic, but soon also direct from the Greek. They opened up entirely new prospects for philosophy and natural science. And the orders, although primarily founded for pastoral and apologetic purposes, displayed such intense spiritual energy that they did not confine themselves to the exclusive task originally assigned to them but, as *ordines studentes*, soon took possession of the young universities, pursuing the paths opened by Aristotelianism. Broadly speaking Oxford became the domain of the Franciscans and Paris that of the Dominicans.

One of the reasons why Aristotelianism had such a great impact on medieval thought was that the Italian Dominican Thomas Aquinas (1244/5–74), continuing the work of the English Franciscan Alexander of Hales (1170/80–1246) and the German Dominican Albert von Bollstädt (Albertus Magnus) (1193 or 1206/7–80), created a synthesis between Christian dogmatism and Aristotelianism, as a result of which the Stagirite's doctrine came to exert a much greater influence on the general outlook on life than it could ever have done on the strength of its intrinsic merits.

This had serious consequences for cultural history in general and for natural science in particular. The close relationship thus established between Christian dogmatism and Aristotelian philosophy imparted as it were a religious sanction to the doctrine of nature implied in the latter. This made it extremely difficult for its students (almost exclusively of the clerical order) to escape from Aristotelian influences and entangled them in numerous problems concerning the relation between faith and science.

The absorption of Aristotelianism into the medieval Christian world view did not pass off smoothly. There were various papal denunciations of the study of Aristotelian ideas at the universities, and the conception advocated by Thomas that Aristotelianism could supply the true philosophical basis for Christian theology did not triumph over other views until the end of the thirteenth century. The canonization of Thomas in 1323 constituted its official recognition.

On the face of it it would seem that Platonism, surviving in christianized form in Augustine's theology, was a much better philosophical basis for Christian dogmatism than Aristotelianism. In its doctrine of the eternity of the world in the past and the future, Aristotelianism implied absolute denial of the Christian
philosophical basis for Christian dogmatism than Aristotelianism.
interpretation (taught by the Arabic philosopher Ibn Rushd, Averroës, 1126–98) which regarded all spiritual life as the manifestation of a single intelligence comprising all individual intelligences and which therefore denied man's personal responsibility for his actions, it conflicted with Christian conceptions of personal immortality and personal responsibility. Thomas must have found it very difficult to convince his contemporaries that, despite these objectionable elements, Aristotelianism was nevertheless capable of fulfilling the function in Christian theology which he assigned to it. As late as 1277, a few years after his death, Augustinian opposition to Thomism was strikingly expressed in the famous decree in which the Bishop of Paris, Étienne Tempier, (second half of thirteenth century) condemned 219 philosophical and scientific tenets, including twenty proclaimed by Thomas. The Bishop, however, seems to have acted more or less on his

own authority; the Church did not confirm his pronouncements and the decree was revoked in 1325. It is, however, of great historical significance as a symptom of Christian opposition to Aristotelianism. An important example is the condemnation of theses which hold that God is not capable of doing certain things, e.g. bringing the entire heaven in rectilinear translation, because if He did a vacuum would remain (which is impossible according to Aristotle). The opponents took offence at this restriction of God's omnipotence on grounds derived from Aristotelian philosophy.

Opinions vary as to the true historical importance of Tempier's decree. Some regard it as merely a quarrel among theologians which was of no importance for science; according to others, it was a symptom of the tendency of the theologians to tutor scientific thought; others again look upon it as being to a certain extent the beginning of modern science, because in principle it rejected subjection to Aristotelian philosophy and gave scholars the freedom of considering other possibilities of thought. It is of course difficult to decide which of these views is nearest the truth. The most instructive conclusion may perhaps be that even after 1200 (before this date it was of course out of the question) medieval thought showed no such servile submission to Aristotle as is still sometimes believed. This conclusion is supported by many other observations. Medieval universities were, especially in the thirteenth and fourteenth centuries, characterized by an extremely animated interchange of thoughts on scientific subjects, testifying to a great variety of views and including criticism, and if necessary rejection, of Aristotelian ideas. All this was admittedly often no more than indulging in polemics for its own sake; none the less, an appeal to human authority in worldly, thus also in scientific, matters was repeatedly rejected on principle and the use of theological arguments in scientific questions met with disapproval.

That the Aristotelian conception of nature ultimately predominated was primarily owing to its intrinsic convincing power. It should be borne in mind that medieval thinkers did not initiate scientific investigation. Greek systems of philosophy embodying scientific theories were handed down to them ready-

made. One of these, Aristotelianism, not only became closely linked up with theology, but was specially convincing because of its systematic structure comprising all spheres of profane knowledge and because its pronouncements on physical and astronomical phenomena tallied particularly well with what seemed to be obvious from unbiased observation and common sense. All this was bound to create the impression that the truth about nature was to be found here. Taking into account the general respect in which Greek wisdom was held in the Middle Ages (a remarkable fact in itself, since it was based on pagan conceptions) and the prevailing easy credulity, it is not surprising that Aristotle's authority was exceptionally great, even for those who criticized him on details.

When in the fifteenth and sixteenth centuries scholastic thought petrified in tradition and routine, the acceptance on intrinsic grounds certainly often degenerated into formal submission to established authority. Aristotelianism then actually became the oppressive bond which according to some current opinion it had been from the outset and rightly aroused the feelings of hostility so frequently evinced by all those who aimed at innovation of thought about nature. But there was no question of all this in the thirteenth and fourteenth centuries.

It was only to be expected that the superseding of the Platonic views of nature prevailing in the twelfth century by those of an Aristotelian trend in the thirteenth should have a stimulating effect on natural science, Aristotle being fundamentally much more empirically minded than Plato. According to Plato, the things of sense in the world about us are merely imperfect copies or imitations of the true realities of a transcendent world; according to Aristotle, they are themselves the realities with which natural science should be concerned. True knowledge of these realities can only be acquired from sense perception: there is nothing in thought that has not first been in the senses.

In the Middle Ages there was a good deal of controversy over the question thus raised. As against those who sought true reality in general concepts there were others according to whom it lay exclusively in concrete individual things and who considered

general concepts to be mere names. The latter doctrine derives its name, *nominalism*, from this characterization of the viewpoint which it contests. It will not be surprising that thinkers entertaining nominalistic or related conceptions exerted a favourable influence on the study of science. Nominalism predisposed to attention for the experience of concrete things to be gained through the senses, whereas the opposite doctrine known as platonic realism (a confusing name, because it held that reality lay in ideas, so that it might also have been called idealism) always implied the temptation to aprioristic speculation.

On the other hand it will be clear that too much emphasis on the nominalistic conception involved the risk of mere empiricism, the collecting of facts without the formation of concepts and theories. Natural science did not come into its own until it had learned to harmonize Platonism with Aristotelianism.

After these general considerations of medieval science we shall discuss a number of individual scholars and special problems without pretending to be complete. In the thirteenth century our attention is in the first place claimed by Robert Grosseteste and his school.

Robert Grosseteste (*c.* 1175–1253), the first chancellor of Oxford University, teacher of the Franciscans and later Bishop of Lincoln, exerted a salutary influence in England and elsewhere by the way in which he organized tuition at Oxford, by his plea for the study of Greek, and by arguing the necessity of placing natural science on a mathematical basis. Nowadays special attention is drawn to him because of his views on scientific method which constitute a first outline of what is now usually called the hypothetico-deductive method: the formulation of a hypothesis based on experience, followed by empirical verification or falsification of conclusions deduced from it. In particular, he formulated the principle of falsification, namely, that a hypothesis should be rejected if it leads to conclusions that prove to be at variance with experience.

He is further of importance for his 'light metaphysics', which considers light as the highest reality in nature. Things of sense

have come into being by the combination of light with primordial matter. Each component was non-spatial in itself, but when the two were combined the visible universe was created by their three-dimensional expansion, as can be demonstrated by blowing a soap bubble.

The key to the understanding of all action of physical force is to be found in the propagation of light, which is the prototype of any extension of an action. This extension is to be expressed mathematically. Grosseteste's views on this matter show affinity with the concept of field in modern physics, but the mathematical instruments at his disposal were altogether inadequate to lead to any definite results of any value.

The metaphysics of light is undoubtedly connected with the great interest in optics displayed by various thirteenth-century scholars. One of the problems studied by Grosseteste was to account for the rainbow, to which attention had already been drawn in Antiquity. On the ground of his falsification principle he rejected existing attempts at a solution without, however, himself proceeding beyond a rather vague reference to refractions of light rays in successive layers of air, clouds, and mist.

In an earlier period of the historiography of the Middle Ages reference would certainly have been made to the Franciscan Roger Bacon (*c*. 1210–*c*. 1293) rather than to Grosseteste, whose follower he was. It was customary for a long time to regard Bacon as the herald of the renovation of natural science, a man who was so far ahead of his time that he was not understood. Special value was attached to his various prognostications of technical achievements which have actually materialized in our time, such as telescopes, automobiles, and aircraft, while he also made a great impression by his fervent plea for a *scientia experimentalis*, which also contained fierce attacks on the scholastic philosophy of his time. Prolonged imprisonment imposed upon him by the direction of his order was moreover an inducement to honour him as a martyr of science.

This representation has not been proof against criticism. On closer examination Bacon makes the impression of being entirely a child of his time. Wishful thinking without any attempt at

substantiating the prospects held out is no longer held in great esteem. It is not clear what he actually meant by his *scientia experimentalis*; it was probably quite different from what is now called experimental science. The reason why he was deprived of his liberty is not known with certainty, but it is hardly plausible that it was an expression of hostility to the study of natural science. What remains is his vehement criticism of almost all his contemporaries, but its substance does not warrant the conclusion that he was ahead of them all. Bacon undoubtedly remains an important and interesting figure in the history of medieval thought, but this is owing to his being its exponent rather than its innovator.

The study of optics initiated by Grosseteste also interested Bacon. Part of what he wrote about it was borrowed from Grosseteste, but he knew an important Arabian source which was not available to Grosseteste: the *Opticae Thesaurus* by Alhazen (see p. 107), which was henceforward to dominate medieval study of optics.

This Thesaurus was also a rich source for John Pecham (or Peckham), a provincial of the English Franciscans and Archbishop of Canterbury from 1279, when writing his *Perspectiva communis*; for the Polish monk Witelo (or Viteillio; thirteenth century) in his work *Optica*; and for the German Dominican Dietrich (or Theodoric) of Freiberg (*c*. 1250–*c*. 1310), who wrote three works on optics. After the invention of the art of printing, Pecham's and Witelo's writings were printed and remained in use up to the seventeenth century.

All three, of course, also dealt with the rainbow. Dietrich made the greatest progress in its explanation; he supposed light rays in water drops to be successively subjected to refraction, reflection on the wall of the drop, and again to refraction. He also clearly understood the formation of the secondary rainbow. Of course he was as much at a loss to account for the colours of the rainbow as any other scholar of Antiquity or the Middle Ages.

The invention of spectacles, so important a factor in later science, is probably to be placed in the thirteenth century. The earliest glasses were for presbyopic people, then followed those

for myopic persons. This was an entirely practical invention; the science of optics did not take any notice of it for a long period. This is in accordance with the general distrust in which scientists held all optical instruments. Natural visual observation, which, as was generally admitted, permitted one to learn the truth, was rectilinear, whether one believed it to consist of rays emitted by the eye, or rays directed towards the eye or paths of *eidola* (see p. 61). Reflection or refraction changed the course of these rays. It was, therefore, to be feared that what was seen with the help of instruments was not the thing itself but an illusion.

If our treatment of medieval physics seems to consist of a series of independent paragraphs, this is simply the natural result of our fragmentary knowledge of this subject, which is constantly increased by the discovery of new manuscripts. Thus, only recently, have we come to know something of the work of the Belgian scholar Gerard of Brussels in the thirteenth century in the field of dynamics, from his *Liber de motu*. He seems to have made use of the *Measurements of the Circle*, written by Archimedes (probably in a translation by Gerard of Cremona) and of a work by Johannes of Tinemue, known to several medieval authors, which was based on Archimedes' *On the Sphere and the Cylinder*. The knowledge of Greek mathematics thus proves to have been more common during this period than we were led to believe formerly. We will not discuss the contents of the *Liber de motu here*.

This is perhaps the most suitable place to say something about Pierre de Maricourt (or Petrus Peregrinus, *c.* 1250) who was probably identical with a scholar whom Roger Bacon abundantly praised as *Dominus experimentorum*. We possess an *Epistola de magnete* written by him in 1269 which, with reference to systematic experiments, deals with the fundamental magnetic phenomena (attraction of iron, distinction between north and south poles, the forces they exert on one another, magnetizing of an iron rod by passing a magnet over it, magnetic induction, and the use as a compass needle). Mention is also made of *terrellae*, the small magnetized iron spheres later to be used by William Gilbert (1544–1603).

The remarkable phenomenon of the attraction of iron by a magnet stimulated the urge for explanation throughout the Middle Ages. The most common theory was that the magnet excites in the iron a property which, striving after union with the magnet, excites *per accidens* a local motion for this purpose. A modern reader may be inclined to observe that such theories only describe the phenomenon in intricate terms, but explain nothing. He is perfectly right, but he would do well to realize that the more familiar phrase that the magnet attracts iron does not explain anything either but only describes what is seen to happen.

The present-day reader will also complain about verbiage if he reads medieval theories on the causes of the origin and the maintenance of the fall of a heavy body. These were traced (i) in or (ii) outside the body. In the former case it was determined to be (i*a*) a tendency towards a specific place (e.g. the centre of the world), (i*b*) as a tendency towards a body (the whole of all heavy bodies). According to (i*a*) a heavy body falls only down on the earth, because the earth contains the centre of the world; according to (i*b*) this happens because it is a 'piece of the earth'.

In the second case it was supposed that this happened because of:

(ii*a*) an attraction by the centre of the world, or
(ii*b*) a repulsion by the sphere of the moon, or
(ii*c*) an impulse by a force distributed throughout the sub-lunar space and directed towards the centre.

The hypotheses (ii*a*) and (ii*b*) were heavily criticized as these entailed an *actio in distans*.

THE SCHOOL OF MERTON COLLEGE

A remarkable group of medieval scholars was that known as the school of Merton College, Oxford. It is generally held that one of the most characteristic differences between medieval and modern physics is that the former was exclusively qualitative, while the latter is predominantly quantitative. Although this

distinction is approximately correct, it should not be taken too literally, because in the fourteenth century there was an endeavour to treat qualities quantitatively while fully recognizing their specific nature. This was linked up with the much-discussed question of how to interpret the increase and decrease in the intensity of a property (a body can be more or less warm, a surface can be more or less brightly illuminated, a human being can be more or less humane). Firstly, what exactly undergoes the change in intensity: is it the quality itself or is there a change in the degree to which the object contemplated shares the quality which itself is considered to be immutable, or does the inherent quality disappear to be replaced by another? Next: is the change to be regarded as an addition or a removal of a similar quality, and, if so, how is an added new quality fused with the old?

At Merton College in the fourteenth century the habit was adopted of expressing a degree of intensity by a number or a letter, first by way of abbreviation, later also as a quantitative indication (the so-called expression *in terminis*) and to make calculations using these symbols. The exact relation between degree of intensity and symbol was hardly taken into account and the method was also freely applied to qualities that are fundamentally incapable of such treatment (e.g. love) or were so at that time (e.g. heat).

The resulting method of treating quality intensities, which was given the name of *Calculationes*, has acquired special importance for the history of science because the variable qualities were also taken to include the instantaneous velocity of a variable motion. This led to the study of various possibilities of changes in velocity, one of the simplest being the regular increase or decrease in velocity with time; hence the case of uniformly variable motion, a concept that was to become of great importance in mechanics.

Scholars working in the field of the *Calculationes* included Thomas Bradwardine (who died in 1349 as Archbishop of Canterbury), Richard Swineshead or Suisset (first half of the fourteenth century), a Cistercian who in the later Middle Ages was generally called Calculator from the title of one of his works, and William

Heytesbury (who in 1371 was Chancellor of Oxford University). All three came from Merton College.

There is no consensus of opinion regarding the intrinsic value of their work. This question will not be entered into here, but two examples will be given.

Bradwardine attempted to formulate the relation between the force setting a body in motion and its resulting velocity which differed from the generally accepted interpretation embodied in the fundamental law of peripatetic dynamics (p. 39). Formulating his reasonings in modern mathematical terms (in doing which we are guilty of an even more serious anachronism than when we wrote the fundamental law as $V = C\frac{F}{R}$), it reads: $V = C \log \frac{F}{R}$.

This formula expresses that, in order to increase the velocity 2, 3, etc., times, it is necessary to raise the ratio of force to resistance to the 2nd, 3rd, etc., power. The formula at once shows that there is no motion unless $F > R$.

This is a most remarkable idea, but its value should not be overrated. It is remarkable in that it is a clear symptom of independence of Aristotle and that it reflects greater freedom in considering functional relationship (hitherto only direct or inverse proportionality had been taken into account). But the above relation is, of course, utterly unfounded; not a single argument based on experience is given and, what is worst of all, it is wrong.

As regards the *Calculator*, we will only mention that his studies of motion led to the summation of infinite series, e.g. $\frac{1}{2} + \frac{2}{4} + \frac{3}{8} \ldots + \frac{n}{2^n} + \ldots$ ad inf. $= 2$

THE PARISIAN TERMINISTS

Another school deserving our attention is that of the Parisian Terminists, a group of scholars attached to the University of Paris in the fourteenth century. Their significance is partly based on an important contribution by one of them to the doctrine of the *Calculationes*, partly on the innovation in Aristotelian kinetics

introduced by them. This will be discussed first, as it is characteristic of the whole group.

As already observed, in Antiquity there had been opposition through the commentator Philoponos to the admittedly highly strained Aristotelian theory that, as soon as a projected body is released by the projector, it is kept in motion by the action of the surrounding air. Instead of this, Philoponos assumed an internal moving power pressed into the body during the projection and then acting as its driving force. Internal moving power is met with in various thirteenth-century authors under different names. The Parisian Terminists completely accepted it under the name of *impetus* and founded on it one of the most remarkable medieval scientific theories.

In a work on Aristotle's *Physica* Jean Buridan (*c*. 1300–*c*. 1385), a professor of the University of Paris, who may be regarded as the central figure of the school, extensively and definitely refutes Aristotle's explanation of the motion of projection and then shows that the impetus theory gives a far less tortuous explanation of all the phenomena discussed. This theory also accounts for the constant increase in velocity during the fall of a body: at first only gravity causes it to fall, but this also imparts to the body an *impetus* which now, as a kind of supplementary gravity (*gravitas accidentalis*) also causes downfall; the motion thus becomes more rapid and the impetus greater. The body is therefore moved by a constant gravity and an increasing impetus. The fact that constant gravity brings about increasing velocity, which had always been an enigma, was thus made comprehensible.

It is remarkable that Buridan also applied the impetus principle to the motion of celestial spheres. When creating the world, God imparted to these spheres an impetus to rotation and, any external resistances being absent, they retain their revolutions to all eternity. It is therefore not necessary to assume that each sphere has been given an intelligence which keeps it going. In deviation from an established Aristotelian principle Buridan here applies a concept derived from earthly natural science to a celestial phenomenon, thus in principle annihilating the fundamental contrast between earth and heaven.

It is of course difficult to express in present-day terms the exact meaning of impetus. As a matter of fact there is no exactness about it. It is as yet a vague conception embodying the germ of later, more exact concepts. It implies something like inertia, something like momentum, and something like kinetic energy. From Buridan's writings one would be most inclined to think of momentum, thus to assume that it is determined by the product of mass and velocity.

The impetus theory was embraced, defended, and extended by three other well-known Terminists: the Frenchman Nicole Oresme, the German Albert of Saxony, and the Dutchman Marsilius van Inghen. Oresme will be discussed presently. The two others are of special historical importance because both were rectors of a university newly founded in Germany (Albert at Vienna in 1366, Marsilius at Heidelberg in 1386), so that they could also disseminate the Terministic ideas there. Albert attempted to formulate a law expressing the manner in which velocity increases during a fall. He thought it was proportionate to the distance covered, an idea which was often to be defended afterwards.

Nicole Oresme, who after holding high offices at the University of Paris and in the Church died in 1382 as Bishop of Lisieux, is mainly of importance for the history of natural science because he used graphical representation in explaining the theory of the change in intensity of properties. He cannot with certainty be indicated as the inventor of this extremely useful aid to science, but we know no older author who used it. And he certainly deserves the credit of having propagated it and of having applied it to an important problem, namely that of uniformly variable motion. By regarding instantaneous velocity as *latitudo* (ordinate) with time as *longitudo* (abscissa) he obtained the figure shown on p. 126 and apparently he knew that the *mensura* (area of the resulting trapezium) represents the distance covered. As this area is equal to that of the rectangle with the same longitudo and the central ordinate as constant latitudo, he formulated the proposition that the path covered during a uniformly variable motion in a given time is equal to that covered in a uniform

motion in the same time at a velocity equal to that of the variable motion at the central moment of the period under consideration.

Until recently this proposition was admired as one of Galileo's important contributions to mechanics. It is, however, at least three centuries older. It may safely be assumed that the Oxford calculators already knew it, but there are no indications that they represented it graphically in a geometric figure, as Oresme did.

Following the example of the French historian of science Pierre Duhem, who in his *Études sur Léonard de Vinci* (1909–13)

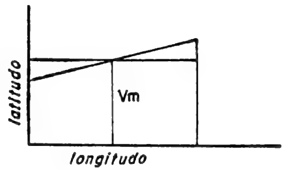


Fig. 10.

was the first to demonstrate the merits of the Parisian Terminists, thus throwing a new light on medieval natural science, some authors call Oresme and the members of his group Galileo's precursors and the above-mentioned rule of uniformly variable motion is called the rule of Oresme. This latter designation is unfair to the scientists of Merton College. Hence we now generally speak of the Mertonian Rule.

The remarkable contributions of the scientists of Oxford and Paris during the fourteenth century have often provoked the question why the new physics were not born in the fourteenth instead of in the seventeenth century. Generally speaking, inquiries into how history would have been if it had taken another course are barren. In this case we must remember that what is called by some the 'scientific revolution' demands a much more fundamental change in the entire trend of thought than the scholastics of the fourteenth century achieved.

Although Oresme may have found an important proposition in the theory of uniformly variable motion later developed by Galileo, he would certainly not have been capable of developing

this theory basing himself on his results. In the first place, the level of mathematical development was far too low. Moreover, there is not a single indication that he was aware that the uniformly variable motion which he studied purely kinematically actually occurs in the important natural phenomenon of free fall. Any physical application of his theory is out of the question.

On the other hand it was certainly known in the later Middle Ages that uniformly variable motion occurs in nature. The oldest reference to it is to be found in commentaries on Aristotle's *Physica* by the Spanish Dominican Franciscus (Dominicus as a member of the order) Soto (1494–1560). The way in which he speaks of it suggests that it was generally known.

A historical inquiry into the perpetuation and any further development of the ideas of the fourteenth-century Oxford and Parisian scholars might be of great importance. It has been surmised that in the fifteenth and sixteenth centuries the University of Padua formed a connecting link between their time and that of Galileo. Various arguments might be adduced in support of this, but the question cannot be said to have been definitely settled.

THE SCHOOL OF JORDANUS NEMORARIUS

A group of essays on statics, the most important of which bears the name of the mathematician Jordanus Nemorarius (*c.* 1220), is not directly related to any of the above-mentioned works. As both his identity and his authorship are still questioned we usually, by way of precaution, speak of the School of Jordanus.

The works on statics are usually presented as partly medieval editions of essays by Euclid. It is quite likely that they are indeed directly related continuations of Greek mechanics. On certain points they had even developed Greek mechanics. Thus we find in these works the concept of the static moment of a force about a point, with the help of which concept the theory of the bent lever is developed.

The most important result achieved by the School of Jordanus is the derivation of the law of the inclined plane which can be found in the *Liber Jordani de Nemore de ratione ponderis*. We

have seen (p. 58) that Greek authors on mechanics did not succeed in establishing this law. Therefore we have here the second case (apart from the Mertonian Rule) where medieval science succeeded in supplementing Greek science.

Jordanus's derivation proves to have been inspired by the Aristotelian proof for the law of the lever (p. 56). It is based on the discussion of simultaneous virtual displacements of two bodies which hold each other in equilibrium by means of a rope and pulley on two inclined planes of a different angle. It is also based on a general principle (later sometimes mentioned as the principle of Jordanus): that which can raise a certain weight G over a height h will also be able to raise a weight $n\,G$ over a height $\frac{h}{n}$.

CHAPTER 8

Medieval Technology and Engineering

ALTHOUGH there is no break between the classical technical tradition and medieval practice there is a deplorable lack of written evidence on the arts and crafts of the Middle Ages, especially during the earlier phase of this period. We have such documents as the eighth-century *Mappae Clavicula de efficiendo auro* (*Key to the Recipe of Making Gold*) and *Compositiones ad tingenda musiva* (*On the Colouring of Mozaics*), Heraclius's *De coloribus et artibus Romanorum* (*On the Paints and Arts of the Romans*) (mainly tenth century) and *Diversarium artium schedula* (Theophilus's *Essay upon Various Arts*) of the twelfth century, but they discuss mainly such arts and crafts as were used for the building and decoration of churches. We have Villard de Honnecourt's sketchbook (1245) with the drawings of many engines, and a few scraps in other documents, but we must derive most of our knowledge from the few actual remains of medieval engineering and such pictures in stained-glass windows or illuminated manuscripts as survive until we reach the fifteenth century, from which period handbooks are still extant.

THE PRIME MOVERS, WATERMILL AND WINDMILL

If medieval technology is deeply rooted in classical tradition it differs in one important aspect, the introduction of prime movers to take the place of muscle energy in moving machinery and tools. The tendency to introduce the watermill in the third and fourth centuries was nipped in the bud by the fall of the Roman Empire and the troubled centuries to come. The migrations of Goths, Vandals, Longobards, Franks, and other tribes were perhaps less dangerous to the future of Europe than the assaults of the Moslems and the Vikings during the eighth and ninth centuries, however after this period Europe recovered and put its house in order.

Slavery had long proved to be an expensive form of production, nor could it ever compete in producing quality goods. Christian charity, its innate respect for manual labour, and its condemnation of slavery were strong incentives to the harnessing of water and wind. Hence when political and social conditions became more favourable there was a tremendous increase in the number of watermills in Western Europe. The *Domesday Book* mentions no less than 5624 watermills in Great Britain in 1086, which counted fewer than 100 a century earlier. A similar picture is shown by documents from central Europe and France. The tenth to twelfth centuries show an 'industrial revolution' which can stand comparison with that of the eighteenth and nineteenth centuries. The same centuries that saw the rise of many a modern city started the mechanization of many crafts.

The watermills, primarily employed for the production of flour from corn, were soon turned to other uses as well. They served for the elevation of water, the pressing of oil seeds, malting, the grinding of ochres and other pigments, fulling, papermaking, and the manufacture of tan, and they moved such tools as hammers, saws, grinding stones, and lathes, an evolution that was practically completed by 1300. Monastic orders such as the Cistercians, those indefatigable reclaimers of barren and waste lands, were prominent in spreading the use of the watermill. Even the harnessing of tidal energy was attempted in France and Italy, but without much success.

Geographical conditions, the constant availability of running water in the streams and rivers of Western Europe, promoted this evolution of the watermill. When in A.D. 537 the Goths besieged Rome and cut the aqueducts, General Belisarius invented the floating mill by placing the machinery of a watermill on a barge which could be floated on a river and was less dependent on the water level. These floating mills were also very popular in medieval Europe and nearly every large town had such mills under the arches of the big bridges. A few survive even to the present day.

A second prime mover, the windmill, became the salient feature of the low windy coasts of north-western Europe. It is often said to have been brought to Europe by the Crusaders.

However, the windmills of the East, which date back at least to the seventh century A.D., had a vertical axle rotated by a circle of sails rigged between two sets of horizontal spokes emerging from the axle. The idea of using the energy of the wind possibly came from the East, but the western windmill seems more likely to have been derived from the watermill; it had a very similar mechanism driven by a horizontal axle moved by a set of vertical sails. Along the Atlantic and the Mediterranean coast such windmills often had between eight and twelve sails, but north of the Pyrénées and along the coasts of the North Sea and the Baltic windmils with four sails only were built from the twelfth century onwards.

The oldest windmill was a fixed structure, the so-called post-mill; later, towermills were built, the cap or top of which could be turned to set the sails in the eye of the wind. The first windmills were nearly all cornmills, but by the fifteenth century they began to figure as prime movers and were gradually put to the same uses as the watermill in countries along the coasts where running water was not easily available. By the middle of the fifteenth century they were applied for drainage purposes in the Low Countries.

It should not be forgotten that in many places machinery was still driven by treadmills worked by men or beasts. They were still to be found in the mines and cotton factories in the eighteenth century and even later drilling rigs in Germany were driven with horsepower, as the mobile steam engines were still too expensive and clumsy.

THE MOBILIZATION OF HORSEPOWER

Very few attempts were made in classical Antiquity to use the full traction power of animals. The faulty arrangement of the breast and girth bands in ancient harnesses exerted a choking pressure on the horse's windpipe. The horizontal breast strap, which may have been introduced into Europe by the people of the steppes, was only slowly appreciated. The great changes came with the substitution of a pair of shafts for the single draught-pole of the wheeled vehicles, the abolition of the girth band, and the

development of the padded shoulder collars from the tenth century A.D. onwards.

Horseshoes of different shapes (some, such as the *hipposandales*, being a temporary protection only) had been known to the Romans and Celts, but their use became general only in the Middle Ages, from the tenth century onwards. They protected the hooves, effected a better grip on the ground, and greatly increased the efficiency of the horse.

Horse-riding also became more fully developed by the interaction of western and eastern influences. The old Roman padded saddle of the fourth century A.D. gradually displaced the more ancient horse cloth and was itself changed through oriental influence into the true riding saddle. Stirrups were adopted by the Viking horsemen of the eighth century from the steppe nomads of the East who had invaded Europe in earlier centuries. Spurs and curb bits were European inventions the use of which became more common in the Middle Ages.

These changes had of course great effects; not only was the riding horse turned into a more efficient instrument of warfare and travel, its importance as a draught animal, notably in agriculture, was greatly improved. The horse began to displace the ox as the 'engine of the peasant' in the course of the Middle Ages, and developed three or four times as much pull as it had been able to exert in the ancient harness.

REVOLUTION IN AGRICULTURE

These changes played their part in the agricultural revolution which was taking place during the Middle Ages. In Western Europe older and different methods of tilling the soil were in use which were better adapted to the type of soil and the climate of the north. Classical methods of tilling proved unsuitable and the northern wheeled plough equipped with coulter, horizontal share, and mouldboard came into common use. This plough made the tillage of rich, heavy river-bottom soils possible even if they were still badly drained at places. It initiated the typical northern strip system of land division, as cross-ploughing was now superfluous.

This new plough needed more power. The peasants began to cooperate by pooling their oxen long before the horse began to pull the plough and thus they laid the basis of the medieval cooperative agricultural community, the manor. When the three-field system was introduced by the end of the eighth century its effects became even more marked. This improved rotation of crops and fallows increased the efficiency of agriculture; there was less ploughing and a larger area under crops than with the old two-field system, which of course was adapted for the dry southern summers. Oxen, consuming the cheap hay, had undoubtedly saved a valuable food, corn or oats, but they were slow. The introduction of the horse in ploughing may have involved feeding it with valuable foodstuffs, but it meant a more efficient use of animal energy and from the tenth century onwards the horse was well established in agriculture.

Mediterranean agriculture underwent great changes when Moslem influences spread along its coasts and introduced irrigation crops such as rice and citrus fruit to Sicily and Spain. These new crops and the techniques connected with them slowly penetrated to southern France and northern Italy. In Europe itself rye and oats became much more formidable competitors of wheat and barley than they had ever been in the south in classical days. On the other hand, viticulture introduced by the Greeks and Romans to Spain and France, which had originally been beer-drinking countries, had come to stay. At the fall of the Roman Empire the vine was already well established in such famous wine-growing districts as the valley of the Moselle, Burgundy, and Bordeaux. Between 800 and 1200 the vine spread to central Europe and even beyond. Apple- and pear-growing had begun to spread by the fifth century A.D. and so had the production of cider and perry, and these were familiar drinks by the tenth century.

If countries like Spain and southern France were lost as beer-drinking countries, the old Celtic beverage was still in common use in western Europe. The older types of beer were flavoured and preserved by the addition of certain herbs or mixtures. By the tenth century hops came to the fore; monasteries

were starting to grow hops, and the slightly bitter hopped beer began to compete fiercely with the older 'fruit-beer' and other types of spiced beer or unspiced malted beverages which were then called 'ale'. By the end of the fifteenth century this long struggle was finally decided by the victory of hopped beer.

Another change can be observed in the increasing production of cheese and butter for human consumption. Butter was known to the ancients, but it had hardly been used except for religious purposes. Cheese and butter now became part of the daily menu of the rich, and were slowly finding their way to the table of the poorer folk.

The art of manufacturing wooden containers and the art of coopering were indigenous to central Europe. In fact the Romans had learnt the art of making tuns and barrels from the Celts of the Alps. During the Middle Ages the manufacture of tuns and barrels took large strides, the pottery containers so popular in classical civilization being replaced by wooden barrels in agriculture and the brewing and wine trades.

LAND TRANSPORT

The worst result of the fall of the Roman Empire was the breakdown of central government. This had a serious effect on land transport which was never completely overcome during the Middle Ages. Roman government had given pride of place to public works, but during the Middle Ages no government was strong enough to enforce or pay for anything which the Romans had achieved in this field. In theory road maintenance was an obligation of the landowners, but this obligation was little observed. Hence the Roman road system, though surviving for many centuries, gradually broke down and by the end of the Middle Ages many such roads had even been broken up by farmers in need of building stone.

The Roman road system survived much longer in the Moslem world, but travel in western Europe had become very difficult. Many towns, monasteries, and officials certainly had their messengers, who sometimes maintained regular services, first on

foot, but from the thirteenth century onwards mostly on horseback. The transport of goods was greatly hindered by the numerous tolls and imposts on roads, rivers, sea, and at market, imposed for the maintenance of roads and traffic, but seldom used efficiently. Gifts of money by municipalities and individuals for the upkeep of bridges and roads were fairly frequent but insufficient. By the fourteenth century there was a growing feeling that the 'King's Highway' should figure largely on the state budget. In general the old Roman road system survived, but new highways became necessary when important shrines at Rome, Compostela, and other places began to induce multitudes of pilgrims to journey. Developing trade forced certain cities to build new connecting roads. During the thirteenth century the Alpine passes were repaved and improved.

The solid road construction of the ancients was not imitated by medieval road engineers, but they introduced a highway of cobbles or broken stone on a loose foundation of sand, which could more easily expand or contract with heat or cold. Blocks cemented with mortar (*chemins ferrés*) and gravel or broken stone roads on a base of sand or earth and properly rammed were also built.

The two- or four-wheeled carts of the Middle Ages differed little from those of Antiquity. However, shafts came into use on larger carts and wagons, thus allowing the draught team to be arranged more efficiently tandemwise. The front axle was still generally made in one piece with the shafts, but by the end of the Middle Ages a swivel attachment to the chassis through a pivot facilitated turning. Such turning trains appeared first on war engines, and they were only gradually adopted for other carts and wagons. The only new form of vehicle was the wheelbarrow, which is illustrated from the thirteenth century onwards and helped to move goods across the Alpine passes, most of which were still carried by 'colliers' or by pack animals.

WATER TRANSPORT

Most medieval transport by land was actually taking the shortest way to river or coast for, as in Antiquity, water transport was still the cheapest way of moving goods. The barges of Antiquity still sailed the rivers in the Middle Ages, but important changes took place in the building of ocean-going ships as Western Europe became more and more aware of its important Atlantic sea front. Though the many-oared galleys and even the merchantmen of the Mediterranean gradually adopted the lateen sails and used their rowing capacity under favourable circumstances only, they were hardly fit to sail the Atlantic ocean and the stormy northern waters. There is little known about the independent lines on which northern ship-building developed. We have a few examples of the clinker-built Viking 'long-ships' which could even sail to Iceland and to Spain, and we know that built-up sides and a true keel were gradually adopted. Little is known of the construction of the Frisian and Danish warships and even less of the ancient Irish boats.

We have reasons to believe that the large round clinker-built merchant ship setting a single square sail on a mast stepped amidships, the 'kogge' or 'cog' which gained favour in the twelfth century, was simply an enlargement of the round ship which had been in use for many centuries on the North Sea coasts. By the end of the thirteenth century the stern-post rudder made such boats more manageable, and by the same time sailors had acquired the art of sailing to windward with the square sails which in the north were more common than the typical Mediterranean lateen sail (which had come from the Near East to displace the older classical square sail in that part of the seas).

By the fourteenth century a new carvel-built type of ship became common; gradually driving the older types from the seas. However, apart from the stern-rudder, the introduction of the floating magnetic compass was perhaps the most momentous invention to promote sailing the ocean. It was known in the twelfth century, but came into general use about one century

later, its introduction being delayed by such stories as that of the magnetic mountain towards which all ships bearing a compass and iron nails would be drawn to be destroyed. This invention was probably inspired by Arabian stories of the quite different Chinese compass but it was developed on entirely different lines in the West.

THE TEXTILE INDUSTRY

During the Middle Ages the manufacture of cloth was divided amongst a number of guilds. One set of workers combed and carded wool, then it was spun on the spindle from the distaff by others, who turned their product over to the weavers, whose finished cloth was then fulled, finished, and dyed by other craftsmen. As mechanization of several of these operations took place during the Middle Ages and complicated apparatus became necessary for economic production, the banker began to play his part in this picture. Most guilds were seriously hampered by the lack of capital; the banker stepped in to finance the industrialization of the various operations in the textile industry and began to assume the role of the employer and middleman. This was one of the reasons why this industry flourished in such rich countries a Flanders, Italy, and Britain.

One of the first operations to be mechanized was fulling, which had always been carried out by beating or treading the cloth in water with fuller's earth in order to make it shrink and 'felt', thus filling the gaps in the weave, and to scour and clean it. The introduction of the waterwheel provided the opportunity to mechanize this heavy task of the fuller, the water being used to move lift hammers by means of a revolving drum attached to the shaft of the waterwheel, which thus did the work of several men.

The second operation to be mechanized was weaving. In the first century A.D. the Chinese knew the drawloom and the horizontal loom with four or more heddles, both of which allowed the manufacture of the more complicated fancy weaves like twills and satins or damasks. Similar types of looms were used in third-century Syria, but we have no evidence that their heddles were

moved by pedals or treadles. This substitution of hand operations by the foot-controlled heddles took place during the late twelfth and early thirteenth centuries and considerably speeded up the production of complicated fancy weaves.

The third operation to be mechanized was spinning. The whorl or wharve of the spindle was grooved and moved by a band connecting it with a large wheel turned by the left hand. This mechanized the twisting and winding of the yarn, but the twist was still controlled by the spinner's left hand. This primitive 'bobbing wheel', which remained in use for coarse yarns up to the nineteenth century, is one of the early examples of the application of the crank in machinery. The crank, which permits the translation of reciprocal motion into rotary and vice versa, was seldom or never used in Antiquity. It is depicted in the Utrecht Psalter (A.D. 850) as moving a grinding-stone and it appears in hand querns. This principle was applied to the bobbing wheel and to the lathe (operating with a treadle) in the thirteenth century. The further evolution of the bobbing wheel is obvious. In the course of the sixteenth century it was no longer moved by hand, but by foot by means of a treadle, thus leaving the spinner's hand free. During the fifteenth century the twisting and winding operations were enabled to proceed simultaneously by the introduction of the flyer to the spinning-wheel making the so-called Saxony wheel.

Another important invention was that of a machine for throwing silk, made by Borghesano of Bologna in 1272. This is an excellent example of the way in which trade secrets were carefully kept in those days, for not until 1538 did its construction become known in Florence and other Italian centres for the manufacture of silk weaves, and they in their turn kept it so secret that it was not until the seventeenth century that it reached England, although the machine had been described by Zonca about 1600. The improvements in fulling, spinning, and weaving were only possible when the fullers and other experts moved out of the towns in search of water for their wheels and thus freed themselves from the conservative economic policy of the guilds.

CAST-IRON AND GUNS

Equally important changes took place in the field of metallurgy. The Middle Ages represent that phase of the Iron Age in which iron definitely triumphed over copper and bronzes as the common metal in daily life. During this period new mines and smelting sites were established beyond the borders of the former Roman Empire and slowly a literature on mining and metallurgy was created, first for the goldsmiths applying metals in art and decoration, then for the experts. Coal was being mined in many places in Europe from the twelfth century onwards to be used on a fairly large scale for certain preliminary metallurgical operations, but the final smeltings were still carried out with charcoal, though this fuel became more and more expensive with the shrinking forests.

The application of water power to metallurgy during the eleventh and twelfth centuries not only mechanized the crushing of ores and other operations; it provided a means of supplying larger volumes of blast air to the smelting furnaces by means of water-moved bellows. Not only was the crushed and washed iron ore now smelted directly into a 'mass' (or bloom) of pig-iron, which was then further smelted and refined to wrought-iron or steel, but in certain types of furnaces which were high enough to keep the contents for a long time at high temperatures the pig-iron could absorb sufficient carbon to liquefy. This 'cast-iron' did not become readily available until the fifteenth century, for its handling required new techniques which took a century to develop. This liquid product could be handled like the bronzes with which the metallurgists had already been familiar for centuries. In addition to this cast-iron, wrought iron of various qualities and steel were produced. The latter product was obtained either by crucible processes or in certain types of furnaces, but it remained a very expensive type of iron. Steel was in great demand by the makers of arms and tools, and metal inlay-workers; the last were often immigrants from the Near East or had learnt their trade from the invaders from the East who were particularly

clever in cloisonné and inlay techniques. The very sophisticated Eastern damascening techniques were adopted and improved even in Carolingian and Merovingian times and they were practised in many centres in Spain such as Toledo.

The production of cast-iron was of great importance for the manufacture of firearms, which gradually displaced the older catapult and sling artillery based on Hellenistic and Roman models. Incendiary mixtures, containing saltpetre, light petroleum fractions, and other ingredients, had been known in the East fairly early and the Crusaders had brought back reports about the terrifying 'Greek Fire' and similar weapons used by the armies of the Moslems. How the well-kept secrets of their composition got around is still a mystery, but variants of gunpowder and the like cropped up at various times at different places in the world. It would seem that true gunpowder consisting of finely divided carbon and saltpetre (to which flowers of sulphur were later added) was invented on the lower Rhine between 1320 and 1330. Forged wrought-iron or cast-iron 'bombards' came into use about that time, mostly to be replaced by cast bronze arms by 1350. A generation later the correct techniques of casting iron guns had been worked out and early in the fifteenth century such guns were cast directly from the furnace into the mould. The technique of 'iron-founding' spread quickly to north-eastern France, Italy, and beyond, and neither firearms nor cannon balls were generally forged any more.

Cast-iron also proved its merits in other fields and may in general be said to be characteristic of medieval metallurgy. The drawplate for iron wire was invented during the tenth century and descriptions of wire-works began to appear in medieval documents. There was also development in the production of hand-arms, scythes, and steel needles, which came into use during the fifteenth century. Special types of iron or steel were sent up and down the trade routes of Europe. Here again we find that as more elaborate furnaces, forges, waterwheels, and the like were needed bankers stepped into finance and organize the trade with which the guilds themselves could hardly have coped.

The introduction of artillery and firearms had two important

effects on the development of technology. Artillery led to the study of the path of a projectile and other problems of ballistics, which stimulated the study of gravitation, percussion, and other questions connected with mechanics, the solution of which went far beyond serving warfare alone. This technical invention was one of the factors gradually interesting the scientists in the work of the craftsmen and promoting the cooperation between science and technology.

The introduction of firearms also brought to the notice of the authorities the need for standardization of tools and parts. The earliest guns each had their own series of cannon balls, but the army authorities soon became aware of the immense value of interchangeability of guns and ammunition, which became even more pressing when firearms were given to foot soldiers and cavalry. The standardization of arms was soon followed by standard drill and uniforms. Standardization of parts also became a necessity for the fleets that sailed the oceans and built up stocks of such spare parts at victualling stations along their route.

NEW LAND FROM THE SEA

From the tenth century onwards a start was made in western Europe with the attack on forests, marshes, and the sea in which religious houses like the Benedictines, Premonstratentians, and Cistercians played a large part. New civil-engineering techniques were thus acquired. Between the seventh and eleventh centuries large parts of the Low Countries were fairly well safeguarded by dykes against inroads of the sea. In many parts of these regions the saltings and flats on the seashore were consolidated by planting glasswort, sea-starwort, and salting grass and finally wrested from the sea by proper dykes. The 'dikemasters' soon learnt the techniques of consolidating these dykes with clay, reeds, seaweed, and the like, and providing further protection by erecting a pallisade in front of the dykes.

The seepage and rain water inside these enclosed stretches of land or 'polders' had to be drained at regular intervals. From the twelfth century onwards a series of canals were dug in these

polders and other low-lying districts and the river dykes were strengthened. The drainage water was led to the sea at ebb-tide by means of sluices built into the dyke, or sometimes by means of weirs. Such weirs and sluices were of course a hindrance to water transport, which soon began to use the drainage canals as a convenient means of reaching all parts of the country. Although inclined planes were built to haul the boats over the weirs, travelling down the weir on the current was not feasible for larger barges.

This situation gave rise to the invention of the pound lock, probably independently in the Low Countries and Italy. The twelfth-century row of sluices near Damme gave way to a real pound lock in 1394–6, but an earlier pound lock seems to have been in use at Spaarndam near Amsterdam about 1315. By the end of the fourteenth century such pound locks were in common use in these regions. In Italy the evolution was different, for there the pound lock arose from the fact that the rivers and canals near Milan could only be made navigable by a series of weirs and flash locks. During the fifteenth century several engineers helped to develop true chamber locks. Leonardo da Vinci (1452–1519) is responsible for the invention of the mitred gates and the wicket which made the handling of pound locks for shipping much easier.

Primitive types of dredgers like the 'water-harrow' were in use in the Low Countries by 1435, but they did not develop into really useful instruments until a century later.

TECHNOLOGY IN EVERYDAY LIFE

Hardly any progress was made in improving the amenities of life during the Middle Ages. The only light sources were still the torch, the candle, and the oil lamp. Good beeswax and tallow candles were now available, but they were mainly used in churches and the houses of the rich; the poor used oil lamps or went to bed early. Neither did the latter profit from the invention of spectacles around 1290, because for a long time they remained too expensive except for the very few. The open firearms of the

hearth was still the only means of heating the house, tile-covered stoves becoming more common in central Europe by the end of our period.

Neither were there any great changes in food. Butter took the place of oil in the houses of the rich, but the poor used rape-seed and colza oil, beef fat, or lard. In general bread, vegetables, and fish formed the mainstay of medieval diet, meat appearing irregularly on the table even of the rich. A large part of the cattle had to be slaughtered and the meat preserved during the winter-time, for there was not sufficient hay production to tide them over the winter in the stable. Pickling and salting or smoking had been inherited from the ancients, but an innovation contributed to the supplying of inland districts with cheap fish. About 1330 Willem Beukelszoon pioneered the gutting of herrings, which operation allowed the salted herrings to be kept for much longer periods.

Wine, beer, and ale were the drinks of the masses, but the discovery of the distillation of alcohol enabled the pharmacists and distillers to produce strong alcoholic drinks which began to displace the older beverages and introduced drunkenness, which had been practically unknown before. Forks were coming into use during the twelfth century, as were buttons, which changed fashions considerably.

Soap, a Celtic invention still new to Pliny, was used for washing clothes from the second century A.D. onwards and the use of soap made such strides that by the seventh century the soap makers in Italy were numerous enough to form a strong craft guild. By the thirteenth century the use of soap was well established all over Europe and the demand continued to exceed supply, which depended on the availability of plant ashes, the only source of lye then available in Europe and already in great demand for glass-making. These ashes, with water, tallow, and olive oil or burnt oil, were boiled and sometimes mixed with bean flour. Green or black soap was thus made, and perfumed soaps were produced for the rich by the sixteenth century. White soap only became available when better qualities of alkali were produced.

Good supplies of water were scarce, as not all towns had

Roman aqueducts and even those were not always kept in proper repair. Most of the water was taken from wells or rivers, but as public sewers and street cleaning were no longer properly surveyed, hygienic conditions fell much below the standards of Imperial Rome. Only during the later Middle Ages did the state or municipal authorities begin to spend money on proper water supply and the first water-driven pumps were installed, indications of the coming change from gravity-flow systems to pressure systems.

In most European towns, the paving and cleaning of streets was not undertaken until the fourteenth century, and the streets were rarely lit at night, the citizens having to carry lanterns to find their way. However, time was beginning to play a more important part in daily life as spring- or weight-driven clocks were constructed. Such mechanical clocks were built in church-towers during the thirteenth and fourteenth centuries. Smaller timepieces for private use came into general use by the end of the Middle Ages.

NEW DECORATING TECHNIQUES

The Middle Ages learnt to produce much better glass and glazes by their contact with the Arab world and thus indirectly with the Far East. Faience and majolica wares were produced and these better types of pottery not only enabled the chemists to handle such corrosive liquids as strong acids, but also provided the household with better and more beautiful pottery which began to displace the more expensive pewter vessels and plates.

Glass was also produced on a much larger scale, prompted by the demands for stained-glass windows for churches. In the north glass first played the part of the mica or alabaster slabs in southern countries. Window-panes were still produced by casting and drawing blobs of glass or by blowing a tube, which was cut open and flattened, but no large panes could be produced this way and medieval windows were often built up of a series of small panes held by a wooden latticework. Glaziers produced stained-glass windows for churches, by using coloured pieces of

glass held and strengthened by lead ribs, which formed part of the design of the window.

Glass was produced in such centres as Murano (near Venice), where the ancient art of annealing glass was perfectly understood and from where it spread to France and Germany. Special laboratory pottery and glassware were produced in several towns of Italy and Germany.

Decorating techniques were demanded by the architects who illustrated the church and chapel walls for the benefit of the unlettered masses who could not read the Latin Bible. Most of these paintings were executed on plaster grounds or gessoed panels. Gesso was a mixture of chalk, gypsum or plaster, and glue or gelatine. Egg tempera paints were applied to it. True fresco painting, i.e. painting on wet plaster, spread during the thirteenth century and new types of paint consisting of pigments mixed with glair and gum were produced. Painting received a new impetus by the use of oil paints. These mixtures of pigments with drying oils were discovered in Italy and reached Flanders about 1400, when the Van Eycks began to use these new techiques and made them famous. Apart from the many dyes and pigments known to the ancients, new ingredients were obtained and older forgotten processes, such as the preparation of white lead from lead and vinegar, and materials, such as vermilion, were rediscovered.

PAPER AND PRINTING

Parchment was still the principal material for documents and illuminated manuscripts, but the art of papermaking slowly penetrated Europe from the Arab world. By the middle of the fifteenth century its production was definitely established and it was pushing vellum and parchment from the market. Luce has stated that the 'popularization of the linen shirt in the fourteenth century marked not only an obvious advance in personal hygiene, but also gave an impetus to the manufacture of rag paper and thus to literature.'

This may be an overstatement, but certainly the coming of paper was shortly followed by the invention of printing. What we

usually denote by this name is in reality a combination of two separate inventions. One was the art of producing books by block-printing, which perhaps came to Europe from China by way of the steppes or via the Arab world, though no proofs for this theory have as yet been discovered. The oldest books printed from blocks in Europe date from 1470. The second invention was that of printing with movable types. Printing with interchangeable, replaceable letters cast in metal was another step towards the mechanization of industry. The reproduction of texts even in unknown languages now gradually became a mechanical operation of producing and arranging the necessary type. Gutenberg is usually hailed as the inventor of metal movable type, though Laurens Jansz. Coster of Haarlem is a serious rival for the honour. Anyway the first printed books produced around 1454–5 mark the end of a period in which information, especially for craftsmen and engineers, was difficult to obtain and dissemination of inventions was slow.

CRAFTSMAN AND ENGINEER

The ancients had known that the craftsman would not be able to develop his craft if he did not combine theoretical and practical knowledge. Thus Vitruvius and later authors describe the architect as one who should be the 'planning architect and surveyor of works'. The need for such engineers as leading craftsmen was recognized, but no steps were taken to educate them. After the fall of the Roman Empire such cries ceased altogether, the craftsmen still being left to educate themselves. Thus after the tenth century the architect was often referred to as *artifex* or *caementarius* (bricklayer), in other words he was simply a master craftsman. Only by the fourteenth century do we find the word architect used again in the sense of designer, planner, and organizer of building activities. The technical ingenuity shown in the early Middle Ages was fettered on the one hand by the conservative policy of the guilds, on the other hand by the impotence of the scientists to grasp the laws of Nature and to formulate them in such a way that the craftsman could use them. Techniques

spread only by migration of artisans, handbooks were not readily available, and the craftsman had to judge and construct according to his own experience. He knew cams and cogs and other machine parts and materials but did not understand their interaction properly and could not assess the strength of the materials he worked with; in short he had no applied mechanics at his disposal to help him. When brother John the Carpenter constructed a new horse-mill at Dunstable in 1295, he found that his claims that it could be turned by one horse were not fulfilled. Four horses could hardly move it! The machinery of early watermills and windmills shows that friction was hardly recognized and that the costly wear and tear of cogs and cams could easily have been overcome by using far more cams on the same wheel than was usual.

If a craftsman through applying his experience had at last invented a good tool or machine, secrecy was the only way of reaping the fruits. Only in the thirteenth century was an inventor occasionally given a privilege to exploit his invention. The state of Venice was the first to provide legal protection for inventors (1474).

The master craftsmen were to make themselves understood in the century which followed the invention of printing; their efforts began to attract attention, and the interest and co-operation of scientific circles established and was developed.

CHAPTER 9

The Renovation of Astronomy

ASTRONOMY IN THE MIDDLE AGES

It is no exaggeration to say that Ptolemy dominated astronomy up to the sixteenth century. This should, however, not be understood to imply uncritical submission to his authority. His system was checked, supplemented, and, if necessary, contested on points of detail; certain foundations of his system were opposed on principle. But his intrinsic authority, which was based on the qualities of his admirable work, was too great to be seriously impaired. There was a gradual improvement in the ephemerides (tables containing a calendar of days and providing astronomical data regarding the positions of the sun, the moon, and the planets) computed on the basis of his system, but before the sixteenth century they were never deduced from theoretical assumptions other than those he advanced: the astronomers' task consisted in calculating tables, the system on which they were based being taken for granted.

From the historical point of view it is interesting to be informed of the checking, supplementation, and criticism referred to above. It would be beyond the scope of a concise work like the present to deal with these matters in detail. Confining ourselves to the main points we shall first discuss Arabian astronomy.

As early as the ninth century the *Almagest* was translated into Arabic and explained and made accessible in a work by the astronomer Alfraganius (ninth century). In the same period Thābit ibn Qurra put forward a historically important new theory of the precession. According to him equinoxes have no steady progressive but oscillatory motions on the ecliptic. His theory is therefore called the trepidation theory.

Astronomical observations in various observatories were made with instruments taken over from the Greeks and improved in

efficiency and design. Special attention was paid to the astrolabe, which was gradually developed into a universal instrument of observation.

The most important of all Arabian astronomers was al-Battānī or Albategnius (*c.* 858–929; see p. 106) who on the strength of his measurements improved many values of astronomical constants stated by Ptolemy. One of the facts established by him was that the apogee of the solar orbit, which in the *Almagest* had been found in Gemini 5° 30′, was in Gemini 22° 17′ in his time. Although this change was partly accounted for by the precession, the remaining difference pointed to the apogee having a distinct motion of its own.

Continued observations resulted in the occasional appearance of new ephemerides, such as the Toledan tables prepared by al-Zargâlî or Arzachel (1029–87).

The first and only opposition on principle to Ptolemy dates from the same time as these tables, the period when science flourished under the caliphate of Cordova. It was aimed at his assumption of circular motions of celestial bodies round centres other than the earth, this being considered to be at variance with the basic principles of the Aristotelian doctrine. This criticism was mainly voiced by al Bitrûğî or Alpetragius (second half of the twelfth century). Linking up with Eudoxus's theory of concentric spheres he developed a world system of his own which was intended to replace that of Ptolemy. However, as it was never worked out in detail and never led to the computation of tables, it cannot be said ever to have been in serious competition with Ptolemaic astronomy.

A very important contribution to astronomy by Arabian scholars was the development of its essential ancillary science, plane and spherical trigonometry. Arabian mathematicians had taken over the sine as a measure of an arc from the Indians and substituted it for the Greek chord; they had also assigned other goniometric functions to the sine. Through the efforts of various mathematicians and astronomers, especially al-Battānī, Abū al-Wafā (940–*c.* 997), and Nāsir al-din-al-Tūsī (1201–74), trigonometry became an independent science which reached such a

high level of development that it could later on simply be taken over in the West. Nāsir al-din-al-Tūsī was the head of an astronomical observatory founded at Maragha by the Mongolian ruler Hūlāgū il Khān (Ilkhān of Persia). The results of the observations made there were incorporated in the Ilkhanian tables (1272).

After this brief review of Arabic astronomy that of the Western Middle Ages can be even much shorter. In 1175 Gerard of Cremona translated the *Almagest* into Latin. In view of the very low level of mathematics in Western Europe (which had not nearly approached the development reached in contemporary Arabia) he added a simplified summary of its substance. For some time to come such compendia were to be the only source for studying Ptolemaic astronomy. One of these in particular, the mediocre *Tractatus de sphaera* by Sacrobosco (John of Holywood, d. 1256) was in very wide circulation.

Through a translation of Alpetragius's work by Michael Scotus (1217) the opposition to Ptolemy on behalf of Aristotle also penetrated to the West, where, however, it did not get a permanent following either. With reference to this question some historians speak of a controversy between Aristotle and Ptolemy which ended by Aristotle being ousted from the field of astronomy. This should not be taken too strictly: the Ptolemaic system was and remained thoroughly Aristotelian in essence. The Stagirite's authority was not shaken by the rejection of Alpetragius's doctrine.

Some Western astronomical observers, such as William of St Cloud (second half thirteenth century) and Jean de Murs (first half fourteenth century), also checked and criticized the existing astronomical tables. These were no longer Arzachel's Toledan tables, but the new Alphonsine tables, prepared in 1252 by the order of King Alfonso X of Castile, which had become known in Paris about 1296. They remained in use, together with the Ptolemaic system, up to the sixteenth century.

A subject of great importance for Western astronomy was the calculation of the calendar. In the Julian calendar, introduced by Julius Caesar, the year was made to consist of 365 days, each

fourth year having 366 days, The length of the year was thus fixed at 365 days and 6 hours, i.e. about 11 minutes too long. The difference increased to one day in about 130 years. Each year having taken too long and thus ending too late, the transit of the sun through the vernal equinox was earlier each year. In the long run this disturbed both the relation between agricultural work and the calendar and fixing the date for Easter. This question occupied all medieval astronomers. In the course of time numerous schemes of reform were suggested and considered, but it was not until 1582 that Pope Gregory XIII effected the calendar reform named after him. Apart from the adaptation of the calendar to astronomical events the fixing of Easter remained a difficult problem, which was tackled in a separate branch of astronomy, that of computus.

The question of calendar reform greatly stimulated the interest in, and the study of, astronomy. The same applied to astrology, which was held in high esteem throughout the Middle Ages and which was only opposed by the Church when it was considered to lead to excesses. Also in this respect the West depended on Islamic culture by using works translated from the Arabic. We mention as an example the work of Abū Ma'schar or Albumasar (d. 886) which was frequently consulted.

Medieval astronomy reached its climax in the work of two German astronomers Peurbach and Regiomontanus, with whom this period ended. The former's *Theoricae novae planetarum*, issued in 1472 by the latter's own publishing establishment at Nuremberg, proves that Ptolemaic astronomy had been fully absorbed in Western thought. The *Almagest* itself was published in Latin at Venice in 1515 and in the original at Basle in 1538. Astronomy then profited from the fact that humanistic scholars had traced manuscripts of this work and established the correct text. They included Peurbach and Regiomontanus and also their principal, Cardinal Johannes Bessarion (1395–1472).

Numerous astronomers, not least the two just referred to, had meanwhile arrived at the conclusion that the Ptolemaic system did not represent observations with sufficient accuracy and, in particular, that it had to resort to intricate complications.

The need of drastic reform was felt intensely, but the astronomers were at a loss how to set about it. We shall now discuss the man who succeeded in doing this.

COPERNICUS (1473 – 1543)

Nicolaus Copernicus, canon of the chapter of the Cathedral of Frauenburg in East Prussia, devoted all his activities as an astronomer to evolving a picture of the universe with the sun in a central position, instead of the earth as in the Ptolemaic system.

The idea was not new. As has been said before (p. 52), in Greek Antiquity Aristarchus of Samos had already pointed out the possibility of explaining the daily rotation of the sky on its axis by assuming a daily rotation of the earth on its own axis, and the annual motion of the sun with respect to the fixed stars by an annual revolution of the earth in an orbit round the sun. In fourteenth-century Scholasticism the first part of this theory had formed a topic of discussion. Oresme in particular had argued its astronomical tenability and defended it against theological opposition and against the objections raised to it on the strength of detached observation and Aristotelian physics (which were in agreement in this as in so many other respects).

If the sun, the earth, and the fixed stars had existed without any planets, this altered conception, amounting to the transfer of the observer from the earth to the sun, would not have appreciably simplified the theoretical concept of the universe. That there was such a simplification was on account of the planets. For it proved possible to understand the so-called 'second inequality' in their motions, i.e. the periodical retrogradations with respect to the stars, as the effect of the earth's annual revolution round the sun. The epicycles which Ptolemy had needed to account for this phenomenon thus became superfluous.

It will be shown that this conception is possible for a superior planet P (Fig. 11).

According to Ptolemy, P describes an epicycle with a centre C in such a way that the radius vector CP is invariably parallel to the radius vector from the earth E to the sun S. CP may also be

assumed to be equal to *ES*. The quadrangle *ESPC* is now a parallelogram, thus *SP* is parallel to *EC*. *EC* is assumed to revolve about *E* at uniform velocity. But in this case *SP* revolves uniformly about *S*, while *S* describes a circle with the centre *E*. It may therefore also be said that this is the deferent circle for the epicycle with centre *S* described by the planet *P*. If it be assumed that the

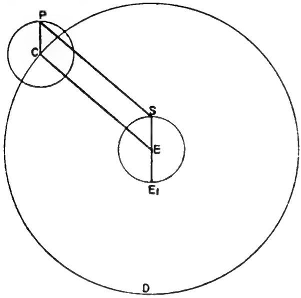


Fig. 11. Transition of the Ptolemaic to the Copernican motion of the planets.

whole system is given at any instant a translation which places *S* in *E*, hence *P* in C and E in E , the situation becomes such that both the earth *E* and the planet *P* revolve uniformly about the sun *S*, which is Copernicus's conception.

The same result is reached (Fig. 12) by plotting *SE* and *SP* at

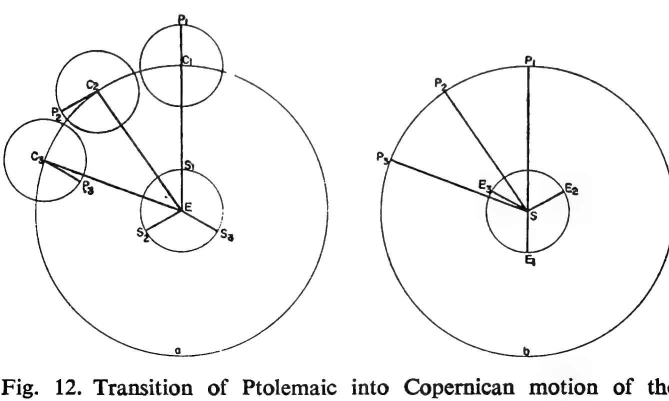


Fig. 12. Transition of Ptolemaic into Copernican motion of the planets.

any instant in true size and direction from a point *S* which is considered to be fixed. This has been done in Fig. 12 for three positions of sun, earth, and planet indicated by the suffixes 1, 2, and 3.

The transition to the new system is even simpler for an inferior planet, because the centre of its epicycle lies on the line earth-sun. If it be taken to be in the sun, a system is obtained in which Venus and Mercury revolve round the sun which is describing its orbit round the earth.

It should, of course, be borne in mind that the above representations are highly schematic; no account is taken of eccentricities and equants. If this be done, the transition from the Ptolemaic to the Copernican system can also be made, but with greater difficulty.

The Ptolemaic and Copernican systems, both simplified as indicated above, can now be placed side by side for comparison (Fig. 13). For the sake of clearness we confine ourselves to an

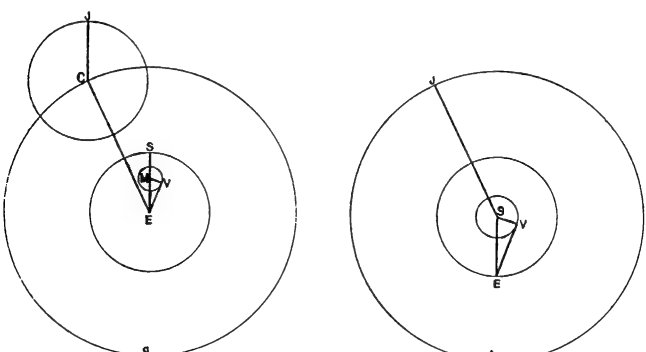


Fig. 13. Comparison of the Ptolemaic (*left*) and Copernican (*right* systems.

inferior and a superior planet, designated by V (Venus) and J (Jupiter).

Copernicus explained his system in this schematic arrangement

in the first book of his work *De revolutionibus orbium caelestium* (*On the Revolution of the Celestial Orbs*), which appeared in 1543, in which he also refuted (in essentially the same way as Oresme had done) objections to a motion of the earth. His principal argument for his own conception was that a simpler and more aesthetic picture of the solar system emerged from it than from the old theory. There were, indeed, no other arguments in his time. He set great store by the consideration that the sun, the predominant influence of which had always been recognized, had at last been given the central place where it belonged.

The only answer he could give to the very strong counter-argument that an annual motion of the earth round the sun would have to be reflected by annual changes in the places of the fixed stars as well as by the epicyclic motion of the planets, was that this effect is imperceptibly small on account of the infinite remoteness of the fixed stars. The answer was correct, but carried little conviction at the time when it was given.

The modern reader who has perused the very comprehensibly written first book of *De revolutionibus* is as a rule disappointed when he has subsequently, in Books II–VI, to go into highly complicated technical–astronomical discussions and calculations in which the celestial phenomena are now actually explained by means of eccentricities and epicycles, and the preparation of tables is taught. Some historians were even surprised to find that Copernicus had relapsed into what one of them deemed fit to call 'the bizarre subtleties of the ancient world system'. On reflection it will however soon be clear that there is no reason whatever for these reactions. The schematic arrangement of Fig. 13 was, of course, not enough for Copernicus to set against Ptolemy's elaborate system and the tables computed by means of it. After his first book he had to start on the technical work proper and for this he had no other aids at his disposal than those used by Ptolemy. The only difference was that spherical trigonometry was available to him because it had become generally known in Western Europe through a book by Regiomontanus. Apart from this *De revolutionibus* might just as well have dated from the second century A.D. because it was entirely written in

the style of Greek astronomy, thus testifying once again to its immense historical importance.

In a way Copernicus was even more Greek than Ptolemy. He adhered even more strictly than the latter to the Platonic axiom, on the strength of which he refused to apply the expedient of the equants (see p. 50) which in fact constituted a violation of this axiom. He regarded it even as his most essential and important achievement that he had succeeded in freeing astronomy from the equants and in again treating it in the true Platonic spirit. But this could only be done by resorting to new epicycles.

During the elaboration of this theory in Books II–VI it is soon apparent that the sun is not at all in the centre of the world, as had been announced in lyrical high-flown terms in Book I. It is as excentric within the earth's orbit as the earth had been in the sun's orbit in Ptolemy's theory. Factually it has but one function, optical – it illuminates the universe. The usual designation of the Copernican system as 'heliocentric' is therefore not strictly correct, but we saw that Ptolemy's system was not 'geocentric' either. As we there preferred the term 'geostatic' we should speak here of 'heliostatic'.

Copernicus's work at first only became known in the circles of astronomical experts for whom, as was emphatically stated in the dedication to the Pope, it was indeed exclusively intended. Very little was noticeable as yet of the drastic change in the conception of the world which the new system was eventually to bring about. One of the reasons for this was perhaps the statement in the preface that the assumption of the earth's motion had only been introduced by way of a mathematical fiction to explain the phenomena, and that there was no intention to assert that the earth actually moves. It was afterwards found that this preface was not from Copernicus himself, but from the theologian Andreas Osiander (1498–1552), who had supervised the printing, and who apparently wanted to forestall the opposition to be expected from the Church.

Astronomical experts could at any rate use the astronomical results to be found in the work without bothering whether the earth actually moved. Thus the astronomer Erasmus Reinhold

(1511–53) computed the 'Prutenian' tables on the bases of the Copernican theory without stating his opinion on the tenability of the theory itself.

Copernicus's work was a very valuable contribution to the development of theoretical astronomy, but it was no great aid in improving the art of astronomical observation and in supplementing the available experimental data. Copernicus confided firmly – too firmly as has been proved – in observations recorded by older authors. This induced him, for instance, to accept the trepidation theory of the precession and even to account for it theoretically in an intricate argument. Progress in observational astronomy was however greatly needed. It was known that theory did not tally with experience (not even in the Prutenian tables). Experimental data were too few and not nearly accurate enough to be used for an exact verification of suggested systems of the universe. Just in time a man was born who was to meet these astronomical requirements: the Danish astronomer Tycho Brahe.

TYCHO BRAHE (1546 – 1601)

The same conviction and tenacity with which Copernicus had worked at the reform of theoretical astronomy were applied by Tycho in his lifelong endeavours to improve astronomical observation. He was the first to see clearly that to obtain experimental data it was necessary to make systematic observations over a long stretch of years, and at the same time to have the means and the energy to carry them out. Aided by a staff of cooperators he continually observed positions of sun, moon, and planets during the period 1576–96 at his observatory Uraniborg in the island of Hven in the Sound. Using new, large instruments which had been very carefully constructed under his directions, and endowed with an exceptional gift of observation, he succeeded in reducing the limit of accuracy of the measurements to 2′, whereas it had been about 10′ for Ptolemy and Copernicus.

Tycho was less successful in the sphere of theoretical astronomy. He was, of course, perfectly aware of the shortcomings of the Ptolemaic system and realized quite well the progress achieved

in the Copernican system. However, partly for theological, partly for physical reasons, he had serious objections to the assumption of the earth's motion. Wishing nevertheless to benefit from the advantages of the Copernican conception he made a compromise by devising a system (known as the Tychonic system) in which he maintained the immobile central position of the earth but conceived the planets as turning round the sun. This was possible, as can be seen from the above discussion of the transition from the Ptolemaic to the Copernican system. Tycho simply stopped at the point where the sun is regarded as the centre of the epicyclic motions of the planets.

The scope of this work generally does not allow the giving of biographical details. An exception has to be made for Tycho, because it was of decisive importance for the development of astronomy that he left Denmark in 1596 and after peregrinations settled at Prague as the Emperor Rudolph II's court mathematician. This brought him into personal contact with the astronomer Johannes Kepler, through whose activities his life work became truly fruitful.

JOHANNES KEPLER (1571 – 1630)

Kepler, a teacher at the Gymnasium of Graz, had attracted Tycho's attention by his *Mysterium cosmographicum* which appeared in 1596 and in which he attempted to advance reasonable grounds for the fact that there were exactly six planets (as a Copernican he regarded the earth as the sixth planet in addition to the five which had been known from of old) and that their distances from the sun had exactly the ratios indicated in the Copernican system. To this end, he had brought the structure of the solar system into relation with the geometric theory of the five regular polyhedra. Although Tycho did not believe in this relationship, he recognized Kepler as a genius. When he settled at Prague he invited Kepler to cooperate with him and Kepler, who as a Protestant was inconvenienced by counter-reformatory measures, agreed to this proposal in 1600.

Tycho directed him to treat the observations of Mars, trusting

that he would do so in accordance with his own compromise system. Kepler however was such a convinced Copernican and also in other respects (e.g. in the conception of the sun's position in the cosmos) differed so much from Tycho that he could not comply with his wishes. Cooperation between them was therefore attended with difficulties. But when Tycho died in 1601, Kepler had a free hand at least in the treatment of the observations of Mars, Tycho's heirs at first objecting to the use of other observational series.

Kepler was now confronted with the task of conceiving for Mars a system of motion in keeping with Tycho's observational data. He naturally tried to do so by using the traditional method, by means of an eccentricity and an equant, as he did not share Copernicus's objections to the latter. At first it seemed as if he would succeed, but when he compared positions computed from his system with the corresponding position observed by Tycho he found a discrepancy of 8 minutes of arc. This would not have troubled Ptolemy or Copernicus. Kepler, however, put so much faith in Tycho's accuracy of observation that this discrepancy was enough for him to reject the system evolved. After attempting for years to find a new system, considerations which cannot even be indicated here induced him to proceed along entirely different lines. After much hesitation he felt compelled, as the first after nearly two thousand years, to renounce Plato's axiom and thus to resort to other than uniform circular motion. Ultimately he arrived at the two laws for planetary motion which bear his name after their publication in 1609 in his *Astronomia nova.*

(i) The orbit of a planet is an ellipse, the sun being in one of the foci.

(ii) The sector of the ellipse which is described by the radius vector sun-planet increases proportionally with time.

This law can also be formulated as follows: the vector describes equal areas in equal times. Or: the areal velocity of the planetary motion is constant.

Kepler's laws constituted a much more drastic departure from ancient tradition than the Copernican system. The renovation of astronomy is therefore sometimes not improperly made to start

with Kepler instead of with Copernicus. There is another reason for this. The subtitle of Kepler's *Astronomia nova: Physica caelestis* ('celestial physics') implied a programme of investigation which sounded paradoxical to many of his contemporaries.

Ancient astronomy had been celestial mathematics: a mathematical description of what takes place in the sky which laid no claim to any physical reality. Copernicus had stuck to this conception, at least in his Books II–VI. Kepler however wanted to do more: he also wanted to explain the phenomena physically. To this end he assumed a field of forces emanating from the sun's ecliptic and acting on the planets. However, since he still believed in the ancient conception of inertia (p. 39) according to which a body can only keep moving when there is a driving force constantly acting in the direction of the motion, he could only explain the planetary motion round the sun by assuming that the sun, and thus the field of force, is rotating. A few years later this rotating motion was actually shown to exist by observations of sun-spots.

Although Kepler's explanation by means of dynamics proved to be untenable, it is of very great historical importance. It was his great merit that he attempted to found celestial dynamics. This constituted a definite break with Aristotle's doctrine, already attacked by the Parisian Terminists, of the fundamental contrast between earth and heaven. Kepler also repeatedly explained details of his theory by the action of forces which were usually of a magnetic nature, a symptom of the very strong influence exerted on the thought of his time by the English physician William Gilbert in his book *De magnete*, published in 1600.

Kepler's view of nature is closely related to the Pythagorean conviction that world order, including music which is also a manifestation of it, could be expressed in numbers. This mode of thought is, even more than in the *Mysterium cosmographicum*, reflected in his *Harmonice mundi* of 1619, where close relationship is established between astronomy, mathematics, and music. Without much connexion with its main theme, this book describes a regularity in the planetary system which is known as Kepler's third law:

(iii) The ratio of the cube of half the longitudinal axis of the orbit to the square of the time of revolution has the same value for all the planets.

The first two laws express how each planet moves; the third teaches something about the structure of the planetary system. The object aimed at in the *Mysterium cosmographicum* was reached at last in the third law. The three laws together were, so to speak, a summary of the experience which the astronomers had gained in respect of planetary motion.

Kepler was of course also faced with the task of deducing astronomical tables from his cosmic system. After endless computations he completed them in 1627 as the Rudolphine tables, which in subsequent centuries were to be the basis of the astronomical description of the solar system.

It would be definitely wrong to think that the Copernican system, in the form given to it by Kepler, soon became common property of seventeenth-century astronomers. The question was for a long time a matter of controversy and it cannot even be said that the astronomers who rejected it were inferior to those who accepted it. In addition to a technical–astronomical there was also a philosophical and general scientific side to the question, both of which continued to give rise to violent clashes of opinion. These have not been dealt with in the above, but we shall revert to them in connexion with the renovation of mechanics.

GALILEO GALILEI (1564 – 1642)

This Italian scientist whose great achievement in physics will be discussed in the next chapter also played an important part in the history of astronomy. For he was one of the first (perhaps the very first) to think of using the telescope (invented about the turn of the sixteenth and seventeenth centuries) to observe the sky. Between 1609 and 1612 he ascertained that the surface of the moon was similar to that of the earth; he discovered that the planet Jupiter had four satellites and that Venus showed phases; he observed a peculiarity in the appearance of the planet Saturn which he described as the triple form of Saturn.

The first three of the above observations he reported in 1610 in his *Nuncius sidereus* (*The Starry Messenger*), which created a great sensation, but which aroused doubts as well as admiration. These doubts are not so absurd as they are often represented nowadays. No one yet understood the operation of the telescope and it is doubtful whether Galileo did so himself. In any case he made no attempt to prove that what he saw in his telescope really existed. The distrust of optical instruments which we discussed before (p. 120) showed up here again.

Galileo also discovered (probably in 1610) the sun-spots which involved him in a violent controversy with the Jesuit Christoph Scheiner as to who had made the discovery first. The same thing occurred with regard to his discovery of the satellites of Jupiter; this discovery was claimed by the German astronomer Simon Mayr (or Marius, 1570–1624). Such disputes may have been of great importance to those concerned, but they are of no great value to us. It seems now quite probable to us that when the telescope had been invented, the idea of turning it towards the heavens may have arisen independently in the minds of different persons in different countries and one and the same observation may have been made about the same time in different places on earth.

His observations with the telescope confirmed Galileo's gradually growing but never openly voiced conviction of the truth of the Copernican theory of the solar system, not just as a mathematical fiction for the simplification of astronomical calculations but as an expression of physical reality. He now began to advocate it openly. This led to the intervention of the Inquisition, which in 1616 declared the Copernican theory to be heretical and which placed the *De revolutionibus* on the Index pending its amendment. The conflict which thus arose and which in 1633 resulted in Galileo being forced publicly to renounce his Copernican conviction cannot be discussed here in detail.

The conclusions which Galileo drew from his observations and which to him seemed to prove the theory of Copernicus were proof only for those who were already convinced of its truth. His opponents could, if they so wished, reconcile the newly discovered

facts with the Ptolemaic system. Galileo also used an argument, in his view conclusive, which was derived from the phenomenon of the tides; he saw in this a clear symptom of the double movement of the earth (round its axis and round the sun). His theory of the tides, however, never met with approval.

ASTRONOMY AND OPTICS

The celestial observations made with the telescope excited interest in the new instrument and led to a study of its operation. Indirectly astronomy thus promoted the development of an important field of physics.

We shall not discuss the invention itself in detail. Tradition ascribes it to the lens-grinder Johannes Lippershey (d. 1619), living in the Dutch town of Middelburg. Others point out that the principle had already been mentioned by the Italian scientist Giovanni Battista della Porta in one of the many editions of his *Magia naturalis* (1589). The instrument is said to have been manufactured in Italy in 1590 and then to have found its way to the Netherlands. It had a convex object lens and a concave eye lens. In physics it is still known as the Dutch or Galilean telescope. From the Netherlands it is then said to have returned to Italy, where Galileo's attention was drawn to it in 1609.

We shall leave aside the question of whether the idea of the telescope was indeed correctly formulated by Porta; his place in the history of optics is in any case established by his *De refractione* of 1593, in which he gave the first theory of the lens, this basic instrument which had long been known but had always been neglected by the students of optics. It is no wonder that, given his ignorance of the true law of refraction and how sight comes about, he did not achieve any conclusions of lasting value.

These were first achieved in the two works which Kepler devoted to optics, namely, *Ad Vitellionem paralipomena quibus astronomine pars optica traditur* (*A Supplement to Vitello in which the Optical Part of Astronomy is dealt with*, 1604) and *Dioptrice* (1611). In the first work he developed a tenable theory of

the lens and of sight. The second work dealt particularly with telescopes. On the basis of his theoretical considerations Kepler gave the principle of the astronomical telescope in which both object and eye lenses are convex. It may seem strange that he succeeded in formulating a theory of lenses and of the telescope without knowing the law of refraction. He believed that a ray of light passing into another medium shows a deviation from the original direction which is proportional to the angle of incidence. If we denote the latter by i and the angle of refraction by r, his law of refraction is as follows:

$$i - r = \mu i \qquad (1)$$

this results in $i = \nu r$ (2)

instead of $\sin i = \nu \sin r$ (3)

However, if thin lenses are used and only rays which make a small angle with the main axis are dealt with (2) will be an admissible approximation of (3). Kepler discusses such cases in his book. The *Ad Vitellionem paralipomena* shows a remarkable similarity to a work *Photismi de lumine* . . . written by an Italian mathematician Francesco Maurolyco, who died in 1575 at a great age. Maurolyco's essay was printed for the first time in 1611 and later reprinted in 1613, annotated by Clavius, and it must therefore have been much older than Kepler's essays. As any dependence in either direction must be regarded as impossible we have here again a curious example of simultaneity of scientific achievements. That these two authors both base their theories on Alhazen detracts but little from the curiosity of this incident.

CHAPTER 10

Physics in the Seventeenth Century
(1) *The Age of Galileo*

INTRODUCTION

AFTER a period of preparation in the second half of the sixteenth century physics began to flourish greatly in the seventeenth century, starting with mechanics, i.e. the theory of motion with rest as a special case. It is not difficult to understand why mechanics should have been the starting point. There was not a branch of the science of inorganic nature in which it was more natural to idealize the phenomena observed by ignoring disturbing circumstances (such as friction and air resistance) and which lent itself so readily to mathematical treatment, a method which was eventually to prove indispensable to all parts of science.

The possibility of studying nature with the aid of mathematics had already been convincingly shown in Antiquity by Archimedes in his deduction of the principle of the lever. When in the sixteenth century his complete works became known in Western Europe (the *Editio Princeps* dates from 1544), he inspired other mathematicians and stimulated them to use his methods in the study of mechanics.

Other branches of physics, such as heat, sound, magnetism, and electricity, were not ready yet for such treatment, being far more complicated and needing more extensive quantitative information. This explains why mechanics, although of fundamental importance and nowadays regarded as a subdivision of physics, could develop as an independent science between mathematics and physics but closer to mathematics. It was never entirely to lose this position. It will therefore be clear why the following paragraphs will mainly deal with mechanics.

SIMON STEVIN (1548 – 1620)

The development of mechanics in Western Europe immediately links up with Archimedes through the work of Simon Stevin, a Fleming living in the Northern Netherlands. In his book *De Beghinselen der Weeghconst* (*The Elements of Statics*, 1586) Stevin first gave a mathematical proof of the principle of the lever which turns out to be a simplification of Archimedes' reasoning. The various applications he made of it jointly amount to a complete treatment of the theory of parallel forces acting on a solid body.

Further, he was original in proving the law of the inclined plane, which had hitherto only been deduced by Jordanus Nemorarius (p. 128). He imagined a cord (Fig. 14*a*) passing over the vertical triangle ABC on which fourteen equal spheres are strung at equal distances and which can slide over the three fixed points P, Q, and R. He raised the question what this *clootcrans* (wreath of spheres) will do when it is released. If it should start moving of its own accord, each sphere would occupy the place of the preceding sphere. The situation would then be the same as before and the wreath would keep moving.* This would result in perpetual motion, which Stevin considered to be absurd. The wreath will therefore remain at rest. This rest will not be disturbed when the part hanging between A and B is removed. Parts AC and BC of the wreath (Fig. 14*b*) will therefore be equally balanced. If these parts are imagined to be concentrated in spheres with weights G_1 and G_2 lying on the inclined planes and connected by a cord passing over a pulley at C (Fig. 14*c*), there will still be equilibrium. These weights are in the proportion of the lengths l_1 and l_2 of the planes and the condition of equilibrium is thus:

$$G_1 : G_2 = l_1 : l_2$$

hence the law of the inclined plane has been found.

* To forestall the objection that, should the wreath move, the spheres would hit the fixed points P, Q, and R and thus be impeded in their motion, it would be better to substitute an infinitely fine string of beads for the wreath of fourteen spheres. The whole experiment (which is purely imaginary) should of course be considered under ideal conditions.

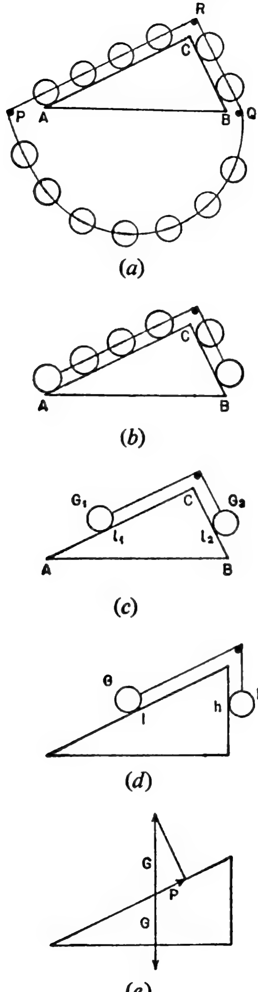


Fig. 14. Explanation of Stevin's wreath of spheres.

It is also seen that a weight G on an inclined plane of length l and height h is kept in balance by a force $P = \frac{h}{l} G$ acting parallel to the plane (Fig. 14*d*). Stevin constructed this force in Fig. 14*e*.

This introduces the triangle of forces, at least for the case of two forces at right angles to each other; the force G in a vertical upward direction which would, of course, be capable of balancing the body with weight G can, if this body lies on the inclined plane, be replaced by a force P parallel to the plane. Further, not quite convincing reasoning leads to the extension of the proposition of the triangle (or the parallelogram) of forces to the general case of forces in random directions. With the aid of this the equilibrium of a solid body with a fixed point is dealt with in full.

Again linking up with Archimedes, but again simplifying the discussion, Stevin devoted the second part of his book to determinations of the centre of gravity, and in *De Weeghdaet* (*The Practice of Weighing*) he put his statics to various practical uses.

In an appendix he made his only contribution to the theory of the motion of falling bodies. He described an experiment made at Delft in cooperation with Jan Cornets de Groot (father of the famous jurist Hugo Grotius) to test the truth of Aristotle's proposition that the time of fall of a body through a given distance is inversely proportional to its weight. They dropped two leaden balls, the one ten times as heavy as the other, at the same moment from a height of thirty feet on to a board and found that the heavier ball did not fall in anything like one tenth of the time of the lighter. On the contrary, it seemed as if only one bump was heard. As this test is described in the *Weeghconst* of 1586, it must have been made in this year or earlier. Although Aristotle's theorem had been contradicted before, it was significant in the sixteenth century that it was tested and proved to be wrong in a special experiment described in print.

In *De Beghinselen des Waterwichts* (*The Elements of Hydrostatics*), which appeared at the same time as the *Weeghconst*, Stevin again continued the work of Archimedes. He gave in it an

original proof of the law of the upward force experienced by a solid body immersed in a fluid which, like Archimedes' proof, is only valid within the framework of Aristotelian physics. He used this principle, for instance, for deducing the hydrostatic paradox (the force exerted by a fluid on the bottom of the vessel in which it is contained is proportional to the area of the bottom, the height of the fluid, and its specific gravity, and is thus in general not equal to its weight). He demonstrated this by means of an instrument which is still in use in teaching physics.

Stevin had written his books *Weeghconst* and *Waterwicht* in Dutch for reasons of principle to show that the vernacular was an equally good (according to him an even better) vehicle of science as Latin, the language which had hitherto been in current use. He was one of a group of scholars distributed over all civilized European countries aiming at the same object for their own languages, such as Leon Battista Alberti in Italy, Robert Recorde in England, and Albrecht Dürer in Germany. Stevin was particularly good at finding or coining pure Dutch technical terms to replace the Latin phrases and thus exerted a strong influence on the Dutch language which is still apparent.

His deepest motive was his desire to make science accessible to all classes of the people and thus to mobilize all available intellectual powers for its study. He clearly foresaw its future enormous significance for mankind and therefore tried to promote its development as much as was within his power.

Unfortunately his works did not become known outside the Low Countries. They became accessible internationally only by a translation into Latin in the collective work *Hypomnemata mathematica* (*Mathematical Memoirs*, 1608), and on a wider scale by the *Œuvres mathématiques* (1634) edited by Albert Girard after his death.

GALILEO GALILEI (1564–1642)

Stevin had imparted a new impulse to the development of mechanics. But mechanics, and with it the entire field of natural science, experienced a much greater and wider influence from his

younger contemporary, the Italian Galileo Galilei, who may be called the central figure in the history of science during the first decades of the seventeenth century. We have no space for more than casual references to Galileo's remarkable career or for the pursuance of the interesting development of his thought from the time that he was first a student and then a professor at Pisa until he published, at an advanced age, the two great works on which his importance for science in particular and his reputation in cultural history in general is based. We shall therefore start with a discussion of these two works:

1. *Dialogo . . . sopra i due massimi sistemi del mondo – Tolemaico e Copernicano* (*Dialogue . . . concerning the Two Chief World Systems – Ptolemaic and Copernican*), Florence, 1632.

2. *Discorsi e Dimostrationi matematiche intorno a due nuove scienze, attenenti alle mecanica e i movimenti locali* (*Discourses and Mathematical Demonstrations concerning Two New Sciences belonging to Mechanics and Local Motions*), Leyden, 1632.

The culminating points of these two works are in the *Third* and the *Fourth Day* (Giornata) of the *Discorsi*, which contain Galileo's definite theory of the motion of falling, and of projected, bodies. In the *Third Day* he gave a definition of the task he had set himself: he would not interfere in the age-long discussions about the cause of the falling motion and its acceleration, but only endeavour to determine its course as accurately as possible and describe it in mathematical terms. He would therefore confine himself to kinematic treatment and avoid any dynamic theories, not because he considered them to be negligible but precisely because of their great scientific importance. Not until it is accurately known how a body falls will it be possible to find the cause of the falling motion with any chance of success.

His starting point was the plausible assumption that a falling body is uniformly accelerated and that this means that its instantaneous velocity is proportional to the time elapsed since the beginning of the fall. His reasoning is that nature does everything in the simplest manner, a maxim which had so often been used in science and which was frequently to be used in future. Increase in velocity cannot take place more simply than in pro-

portion to time. (Galileo did not add that at an earlier stage of his development he had, as had Albert of Saxony (p. 125), conceived velocity to be proportional to the distance covered, which at the time he evidently considered to be simpler.)

Subsequently, with the aid of a graphic representation, he derived the Mertonian Rule in a slightly different manner from Oresme. Galileo formulated it as follows: the time in which a given distance is covered by a body in a uniformly accelerated motion from the condition of rest is equal to the time in which the same distance would be covered by the same body in uniform motion at a velocity amounting to half the sum of the highest and the lowest velocities of the uniformly accelerated motion. In present-day notation this reads as:

$$S_t = \frac{V_o + V_t}{2} t$$

From this it can be shown that the distance is proportional to the square of time and it follows from this that the distances covered in successive equal times are in the ratio of the successive odd numbers. Galileo always attached special value to the latter formulation. Other laws of falling bodies suggested during the seventeenth century or earlier were invariably formulated in this way. Thus Leonardo da Vinci gave as his opinion that these distances are in the ratio of successive integers.

Galileo then wished to test this relation and hence his initial assumption. However, the motion of free fall being too rapid to enable the ratio of distance to time to be measured directly, he considered instead the retarded motion down an inclined plane. The relation between retarded and free fall is established by the 'postulate of equal final velocities', expressing that when bodies descend from the position of rest from the same height along planes of different angles of inclination they will reach the bottom at the same velocity. The mathematically derived law of falling bodies is then verified on a sloping plane and, by making the angle of inclination small enough, the time can then be made as long as desired.

The law can be verified by making a metal ball roll through previously marked distances in a gently sloping channel and

comparing the times. Time is measured by finding how much water forces through small holes in a barrel. Galileo stated that the ratio of the distances does not differ appreciably from the ratio of the squares of the times. He did not give the values observed.

It is for two reasons that we have extensively discussed the first pages of the chapter *De motu naturaliter accelerato* (*On the Naturally Accelerated Motion*) from the *Discorsi*. In the first place, in order to refute two erroneous ideas that are still current regarding Galileo's treatment of the motion of fall. One is that, when considering the values of times measured for distances covered, he discovered that the distances were in the ratios of the squares of the times. The second is that, because the fall takes place under the influence of a constant force, he derived that the acceleration of a falling body must be constant. The first opinion arose from the strange idea that what from a didactic point of view is considered desirable in present-day elementary teaching of physics also represents the historical facts of the development of physics. The second opinion originates from a statement in Isaac Newton's *Principia* which is obviously incorrect, because the dynamics of the motion of fall were not known in Galileo's time. The end of the development of mechanics in the seventeenth century is confused here with the beginning.

Our second reason is that we wish to show with what perfectly clear understanding Galileo applied the method of investigation of natural science at present called the hypothetico-deductive method. It consists in drawing conclusions in a deductive (preferably mathematical) manner from a preconceived hypothesis and then testing these conclusions. If they prove to be correct, the preconceived hypothesis can, for the time being, be accepted as usable. Experiments are therefore not heuristic (to see what happens) but are made to verify the results of a deduction (to see whether the starting point is acceptable). It does not matter how the initial hypothesis was found. Galileo's conviction that nature does everything in the simplest manner possible is as legitimate as any other. It is plausible to surmise that in most

cases this hypothesis reflects the essence of more or less conscious experience.

Galileo applied this method in the *Discorsi* without explaining it. Elsewhere (in his *Il Saggiatore*, *The Assayer*), when referring to this method he called the first part of the procedure in which the hypothesis is advanced *metodo risolutivo*, the second part in which the conclusions capable of experimental verification are deduced from the hypothesis, *metodo compositivo*.

We can be brief about the rest of the *Third Day*. It contains a large number of mathematical propositions relating to motions of fall in vertical and inclined planes testifying to great originality and immense ingenuity, but only occasionally opening up new fundamental physical aspects. Almost immediately after its creation, mechanics begins to detach itself from physics, its source of stimulation, and to pursue a course of its own.

Mention should, however, be made of one point because it was of importance in physics. In a scholium of the 23rd proposition of the *Third Day* Galileo considered a body which, after having descended through a given vertical distance in an inclined plane, rises in another inclined plane with the velocity thus imparted to it as its initial velocity. He argued that it will rise to the same height as it was originally. This result is in fact equivalent to the postulate of equal final velocities and had, indeed, been used in its experimental verification. This experiment had been carried out by making a pendulum, as it passed through the vertical, strike a horizontal pin a little below the point of suspension, and demonstrating that the bob rises in its new path to the same height it would have reached if the string had not been impeded in its course. This was a view which was afterwards to be understood as a special case of the law of the conservation of energy in the earth's gravitational field, assumed to be homogeneous.

It is rather confusing that in a scholium of the second proposition of the *Third Day*, which is strictly kinematic, a dynamic proof of the postulate of equal final velocities should be attempted. Not being preceded by any dynamic axiom, it could not possibly fit in with the system of the *Third Day*. In fact, it was absent from the first edition of the work and was drawn

up later and inserted in the text of the second edition. The lengthy reasoning intended to convert the postulate into a proven proposition is far from convincing. The only admissible conclusion is that the influence of Aristotelian physics on Galileo's views on dynamics continued to be much stronger than would be surmised from the highly polemic attitude he frequently adopted towards Aristotle.

The *Fourth Day* of the *Discorsi* deals with the motion of a projectile in a manner analogous to the motion of fall in the *Third Day*. The projectile is assumed to be discharged with a horizontal initial velocity. The trajectory is found by compounding the uniform rectilinear motion which the body would have if not subject to gravity, and the uniformly accelerated motion it would have in the absence of the horizontal initial velocity. Since in the first case the distance covered is proportional to the first power of time and in the second case to the square, a curve results with an ordinate proportional to the square of the abscissa, i.e. a parabola. As in the formulation of Kepler's first two laws, seventeenth-century science again utilizes mathematical results obtained in Antiquity.

The remainder of the *Fourth Day* is concerned with mathematical problems which cannot be dealt with here, but which give rise to the same comments as have been made on the *Third Day*.

The results proved in flawless mathematical form (also a Greek heritage) in the *Third* and the *Fourth Day* of the *Discorsi* were Galileo's intellectual property long before their publication, because, with many other kinematical propositions they already appear, although they are not proved, in the *Dialogo*.

This work is definitely inferior to the *Discorsi* from a scientific point of view, but surpasses it in broadness of treatment and in importance for cultural history. Galileo wrote it because he wished to continue his earlier attempt to defend the Copernican system in defiance of a verdict pronounced in 1616 by a tribunal of the Inquisition (p. 162). To this end he adopted the method of making the controversy about the Ptolemaic and Copernican systems a topic of discussion in a dialogue. If the partners in the

dialogue made a detached appraisal of the arguments adduced for and against the two systems, it would not be possible to blame the author if the reader should become convinced of the correctness of one of the two. It is an open question whether Galileo could ever have had a chance of achieving his object; the fact is that he did not succeed. The whole work is a downright plea for Copernicus scattered with perfunctory remarks that, as had been settled by the Inquisition, his system could not be right. These remarks were derisive rather than expressing submission. The Inquisition accordingly prohibited the work and called Galileo to account. Thus in 1632 the famous trial started which on 22 June 1633 ended with Galileo's solemn recantation of the Copernican theory.

We cannot discuss the ill-favoured proceedings of the trial or enter into details as regards the impression which the verdict made throughout Europe and its effect at the time (and long after!) on the attitude of many people towards the Roman Catholic Church. We are primarily interested in the way in which Galileo used his scientific views to refute the arguments of a physical nature advanced against the Copernican system.

These arguments chiefly concerned the earth's motion and almost all of them originated in the antique conception of inertia (p. 39). A few examples will be given. If the earth turned from west to east, as had to be assumed to account for the daily celestial motion from east to west as a result of the earth's rotation, a body thrown vertically upwards would have to come down west of its starting point, because during the ascent and descent the earth has proceeded on its way to the east. It would never be possible for clouds and birds to be seen moving east, because the earth's rotation is always more rapid than they. A projectile from a gun would be sent farther to the west than to the east, because in the first case it would move in the same direction as the earth, in the other case in the opposite direction. This last argument had been advanced by Tycho Brahe.

It is quite clear to people who have been brought up in modern science that all these reasonings have one mistake in common: the idea that a body attached to another moving body loses the

motion imparted to it by the other body as soon as contact is broken. According to modern mechanics, in the absence of external causes a moving body can no more come to rest than a body at rest can be set in motion. The property of matter called inertia implies that a velocity acquired by a given body cannot change unless this body is affected by an external cause called force. The antique view of inertia applied to the special case that this velocity was zero.

The extension of the definition of inertia from this special case to the general case was only gradually developing at the beginning of the seventeenth century. This development was primarily due to Galileo's tireless didactic activity chiefly displayed in the *Dialogo*, in which he showed by numerous instructive examples that any body will maintain its velocity if not deprived of it. During its motion of rising and falling a body thrown up from the revolving earth maintains the horizontal velocity which it possessed when it was lying on the ground and the thrower therefore invariably sees it vertically overhead. The situation is the same as when somebody on a sailing vessel throws up a ball vertically. He can catch it again from the same place on the ship. This was so evident to Galileo that he did not consider it necessary to test it. The French philosopher Pierre Gassendi (1592–1655) was the first to conduct such an experiment on board a sailing vessel.

Another objection he had to counter was that nothing could be detected of the alleged motion of the earth. He gives it as his opinion (which may be called his 'principle of relativity') that the phenomena of motion taking place in a set of bodies do not change when a joint motion is imparted to the whole set.

Galileo did not express the principles of inertia and relativity in the correct form given to them in the course of the seventeenth century and definitely formulated in Newton's mechanics. Galileo's principle of inertia only refers to earthly phenomena of motion and implies that an earthly body unaffected by any disturbing influences maintains its velocity unchanged in a horizontal plane, but this horizontal plane is understood to be a spherical surface with the centre of the earth as its centre. Since

over a small distance this may be considered to be a plane surface, Galileo's results are in fair agreement with those of Newton, as for example in the deduction of the trajectory of a horizontal projected body in which the motion due to the horizontal initial velocity is considered to be only approximately rectilinear. A similar case occurs with the principle of relativity. In Newton's mechanics this refers to the case that the joint motion is a uniform rectilinear translation, whereas Galileo did not qualify its nature. This is again of practically no influence on the phenomena which he considers, because they are of short duration.

The above shows the great difference between Copernicus' and Kepler's defence of the heliostatic theory of the solar system and that presented by Galileo. The first two considered it from a mathematical–astronomical point of view, which according to them improves the kinematic description of the celestial phenomena. Galileo treated it as a physicist: he refuted the objections that can be raised to it if it is not regarded as a mathematical trick but as an expression of the physical reality in the universe. It is therefore not surprising that the controversy about the Copernican system did not start before Galileo.

GALILEO'S PREDECESSORS AND FOLLOWERS

The splendour surrounding Galileo's name was such as virtually to obscure the merits of his immediate predecessors and followers, but these merits are nevertheless great enough to deserve mention here.

Giovanni Battista Benedetti, a Venetian mathematician, in his work *Diversae speculationes* (*Various Speculations*, 1585) considered problems of the motion of falling bodies in a manner testifying to independent judgement and a critical mind. In an ingenious argument he showed that *in vacuo* unequal bodies of the same material should cover the same distance in the same time, contrary to Aristotle's thesis that the heaviest body falls the most quickly. For if this were true the body obtained by uniting a heavy and a light body would on the one hand have a velocity of fall intermediate between those of the two bodies (the slower body re-

tarding the quicker, the quicker body speeding up the slower), but on the other hand its velocity would have to be greater than that of the heavier body (the composite body being heavier than the heavier of the two components). This perfectly convincing reasoning is often erroneously attributed to Galileo and represented wrongly owing to the omission of the condition that the bodies must consist of the same material.

Giovanni Battista Baliani, a Genoese patrician, published in 1638 *De motu naturali gravium* (*On the Natural Motion of Heavy Bodies*), which was reprinted on a larger scale in 1646. His explanation of the equality in speed of fall of all bodies *in vacuo* shows his insight into the proportionality of mass to weight. In addition, he did not restrict the law of intertia to the case of horizontal motions on earth but said that it is of universal application. He made an attempt at a dynamic treatment of the motion of a body under the influence of a constant cause of motion which, however led him to Leonardo's instead of to Galileo's law of falling bodies.

Evangelista Torricelli (1608–47) was a famous Italian mathematician, whose name will also be encountered in connexion with the theory of atmospheric pressure. In his work *De motu gravium naturaliter descendentium et projectorum* (*On the Motion of Heavy Bodies which fall downwards naturally and of Projectiles*) he supplemented his teacher's *Discorsi* on various points, for instance by extending the treatment of the trajectory of a projected body to the case of an initial velocity in an arbitrary direction, for which he made use of the general formulation of the law of inertia. He also laid down an axiom for statics which here found its first definite formulation: two united bodies cannot start moving of their own accord unless their common centre of gravity is lowered.

Our observations on Galileo's predecessors and followers are not intended to detract in the least from his immense importance to the development of science in the seventeenth century. They have been made for reasons of fairness. Now that in the treatment of the historical development of thought it is common practice to mention the names of persons who were instrumental in achieving

it (it might also be possible to conceive a historiography dealing exclusively with ideas), honour must be given to those to whom honour is due. Another reason is to show that the contributions of a great pioneer are not always so absolutely new as would at first appear and that, moreover, he does not always realize the full significance of his own discoveries. All the consequences are only realized later by his pupils, to whom he has shown the way, and who find the correct formulation.

WILLIAM GILBERT (1540–1603)

At the end of this chapter, which is almost entirely devoted to mechanics, something should be said about the contributions of Galileo's generation to other branches of physics, at least in so far as they will not be treated later on. The English physician William Gilbert had a great influence on seventeenth-century natural science through his book *De magnete magneticisque corporibus et de magno magnete tellure physiologia nova* (*New Physiology of the Magnet and Magnetic Bodies and of the Great Magnet, the Earth*), which was published in 1600.

Gilbert made use of the knowledge summarized in the thirteenth century by Petrus Peregrinus in his *Epistola de magnete* and of the experience gained later in navigation. By the end of the fifteenth century the magnetic declination (usually called variation) of the compass needle had become known, in the sixteenth century the variability of its magnitude at different places on earth, and also the magnetic inclination. Instruments had been constructed to measure both properties and books had been written on them, e.g. *The New Attractive* by Robert Norman (1581) with an appendix by William Borough.

Gilbert transferred the whole subject of magnetism from the empirical to the scientific. He profited from experience gained in navigation, and also from his extensive practical knowledge of mining and metallurgy. He belongs to the widely distributed group of intermediaries between technique and science who have contributed so much to the creation of modern physics.

De magnete contains in the first place an experimental treatment of fundamental magnetic phenomena which, with the exception of the mathematical formulation, is not essentially different from what is to be found in modern elementary textbooks on natural science. It is remarkable that he did not work with bar magnets but chiefly with magnetic spheres. The name he gave them ($\mu\iota\chi\rho\acute{o}\gamma\eta$ = micro-earth; *terella* = small earth) explains his preference. The new view he wished to proclaim, and which made a deep impression upon his contemporaries, is that the earth is a big magnet, and thus a magnet is a small earth. The sphere was therefore for him the natural shape of a magnet.

In his book Gilbert developed extensive theories about both magnetic and electrostatic phenomena, but they are still entirely in the realm of scholastic science. Although in many respects imbued with the spirit of the new experimental science, he had not progressed nearly so far as Galileo, who had refused to accept any speculation on the essence of things and the deepest cause of natural phenomena as long as it was not known exactly what was happening. Unlike Galileo, Gilbert had no turn for mathematics.

Gilbert's work was immediately successful with his contemporaries. Galileo, who as a rule paid little attention to other people's work, gave an exhaustive account of it in his *Dialogo*. His ideas were frequently used by Kepler in the *Astronomia nova* and by Stevin in his *Van den Hemelloop* (*On the Course of the Heavens*). There was a general tendency to interpret the influences which bodies exert on each other as magnetic actions. This tendency is, indeed, still noticeable at present.

FRANCIS BACON (1561–1626)

There is still no agreement as to whether or not the English philosopher Francis Bacon should be regarded as an important figure in the history of science. On the one hand it is pointed out that he did not make any positive contribution to its development, that the methods he recommended for studying it were never successfully applied, either by himself or by others, and that he understood nothing of the true merits of other investi-

gators. On the other hand, his advocates maintain that, because of his ideas about science and its social importance, he had a highly stimulating effect on the development of thought, particularly because of the brilliant manner in which he expressed his ideas.

Both views are right. If Bacon's name and all his writings were eliminated from the history of science, not a single conception, not a single result would be lost. His suggestion of studying nature by considering lists of experiences compiled by certain prescribed methods from which the answers to questions about natural phenomena would then almost automatically emerge has never produced any results. He failed to appreciate both Copernicus and Gilbert. But many of his brilliant aphorisms were a guiding principle for the work done by numerous investigators, including the greatest. We shall only mention the aphorism from which the sub-title of this book has been taken: *Natura non nisi parendo vincitur* (Nature is only conquered by obeying her). He ceaselessly pointed out the outstanding importance of the experimental method. The development of physics in seventeenth-century England may be regarded as the outcome of his ideas. René Descartes (1596–1650), who was slow to admire others, wrote about him with great appreciation. Christiaan Huygens (1629–95), whose own investigations took an entirely different course, regarded him as the founder of the new science. Both were perfectly aware of the one-sidedness of his exclusively empirical turn of mind and of the inefficiency of his method of using lists. It is significant that they nevertheless held him in high esteem.

Bacon was, indeed, a figure that is not to be neglected or disparaged with impunity, especially because he realized his position very clearly and laid no claim to the rank of a creative investigator. '*Ego sum buccinator tantum*' ('I am only the horn-blower') he said of himself.

Typical of Bacon and again illustrative of his historical importance is his prophetic vision of the coming development of two aspects of the study of science with which we have long been familiar, but of which only few had an inkling at the beginning

of the seventeenth century: the indispensability of team-work and the close relationship between science and technology. The first thought he developed in his utopian *Nova Atlantis* (*The New Atlantis*) in which he outlined a plan for an institute (*Solomon's House*) for organized scientific cooperation of scholars; the second thought is repeatedly reverted to in discussions about the desirability of much closer contact between artisans and manual workers on the one hand and scholars on the other. The worker's handicraft will become more efficient by the application of scientific methods while students of science will widen their horizon and receive many useful suggestions from practical experience. This will ultimately benefit the community; conditions of life will be improved, diseases combated, suffering alleviated, life will be lengthened.

Bacon had this view of the eminent social function of science in common with a few other far-seeing spirits of his time. It was an idea of which nothing had been perceptible in Antiquity and only very little in the Middle Ages. Bacon shared it with Stevin and, as will be seen, with Descartes. Posterity appreciates him because he was among those who conceived the idea of the social function of science and propagated this idea so eloquently.

CHAPTER 11

Physics in the Seventeenth Century (2) *The Age of Descartes*

INTRODUCTION

In the early years of the seventeenth century the importance of mathematics for natural science was being more and more generally recognized, not only for its practical value. Some of the greatest investigators of the period began to realize that it had a much more essential function than that of a useful but perhaps dispensable ancillary branch of science. They expressed the conviction that the identifiable structure of the material world is mathematical in nature and that there is a natural harmony between this world and the mathematical turn of the human mind. *Il libro della natura è scritto in lingua matematica* (The book of nature is written in mathematical language) was one of Galileo's favourite maxims of which he gave many variants. Kepler believed, in conformity with his Pythagorean–Platonic attitude of mind, that God in creating the world was guided by mathematical principles and enabled the human mind to grasp the meaning of these principles. Just as the ear is adjusted to hearing sounds and the eye to seeing colours, the mind is *ad quanta intelligenda condita*, adjusted to understand quantities. Natural science should therefore be studied by mathematical methods. René Descartes followed this idea to its logical conclusion, thus virtually identifying science with mathematics. The human mind begets its knowledge of nature in the same way as that of mathematics.

Descartes was forty-one when he published some of his scientific investigations for the first time. The three essays *La Dioptrique*, *Les Météores*, and *La Géométrie* were preceded by *Discours de la méthode pour bien conduire sa raison et chercher la vérité dans les sciences* (*Discourse on the Method to guide one's*

Reason well and to seek the Truth in the Sciences). This *Discours,* which at the same time is an introduction to his philosophy, came to lead an independent existence in the history of the culture of the mind, and is one of the classical products of seventeenth-century philosophy.

Some of the investigations published in 1637 were certainly much older. During 1618 and 1619, when Descartes completed his education as a young nobleman by serving at Breda in the army of Prince Maurice, Stadtholder of the seven united Northern Netherlands provinces, he was already engaged in scientific investigations and he seems to have conceived the basic idea of analytical geometry developed in *La Géométrie* at about the same time.

BEECKMAN AND DESCARTES

At Breda he cooperated with the Dutch scholar Isaac Beeckman, theologian, physician, and candle-maker, later headmaster of the Latin School at Dordrecht, a man profoundly interested in natural science who was in the habit of entering all his observations and meditations in his diary, the *Journael.* It had long been given up for lost, but was retrieved in the beginning of the twentieth century and it is now accessible in a modern edition.

Under the dates of 23 November–26 December 1618 the *Journael* gives an account of a discovery in the field of mechanics made by the author in cooperation with Mr du Peron (as Descartes called himself after one of his estates).

We shall describe this discovery before discussing Descartes himself. It concerned a subject the historical importance of which will be clear after all that has been written in previous chapters: the deduction of the law of falling bodies, not purely kinematically as in the case of Galileo, but dynamically. An investigation is made of the motion which a body upon being released attains under the action of gravity, which is assumed to be constant.

In his *Journael* Beeckman repeatedly gave an explicit formula-

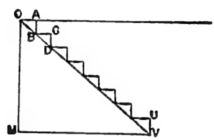
tion of the physical foundations on which the reasoning is based. In his original terminology they read:

(i) *Sij* (i.e. *de zwaarte*) *treckt met kleijne hurtkens* (gravity draws by little jerks).

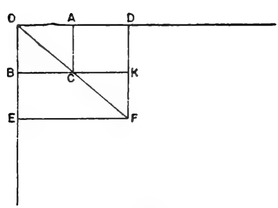
(ii) *Dat eens roert roert altijt, soot niet belet en wort* (what moves once, moves always, if it is not impeded).

The first is the expression of a conception, often successfully applied in the latter half of the seventeenth century, namely the consideration of a continuous force as a periodic percussive power with the period approximating to zero. The second embodies the new idea of inertia which was eventually to replace the Aristotelian basic principle: every moving body is moved by something else.

The reasoning is as follows (Fig. 15*a*):



(*a*)



(*b*)

Fig. 15. Dynamic deduction of the law of falling bodies (Isaac Beeckman).

Suppose that gravity by the first jerk at a released body imparts a speed ω and that a period of time τ elapses before the

next jerk. Representing ω by OA and τ by OB, the area $OACB$ indicates the distance covered in the first period. The second jerk again creates a speed ω, but as the speed acquired in the first period continues to exist, the speed is now $2\ \omega = OD$ and the distance covered in the second period is indicated by the area $KBEF$. Continuing in this way, we find (Fig. 15*b*) the distance covered in the period OM as the area under the stepped line $OABCD \ldots UV$. If τ approximates zero, this area approximates that of the triangle OMV, which immediately shows that the distance is proportional to the square of the time.

Accurate analysis of this note in connexion with what is said elsewhere in the *Journael* by Beeckman and in later writings by Descartes makes it very plausible that the physical fundamentals of the reasoning originated mainly with Beeckman and that Descartes, who had received an excellent scholastic education from the Jesuits of La Flèche, contributed the mathematical aid of graphic representation which enabled the transition to the limit to be made.

Beeckman made entries in his *Journael* throughout his life, but never published them. As a result, he has no place in the factual history of natural science, no more than, for instance, Leonardo da Vinci. This is a pity, because the *Journael* distinctly makes the impression that he was ahead of his time in various aspects of scientific thought. It should be borne in mind that the deduction described above dates from 1619, i.e. thirteen years before the publication of Galileo's *Dialogo*.

DESCARTES

We shall now turn to Descartes himself to describe how he tried to realize the ideal which was for ever present in his mind: to treat natural science as mathematics. A conception derived from his metaphysical system (which will otherwise not be considered in this book) was that the essence of matter consists only in the geometric characteristic of extension: matter is what is spatially extended and no more than that. It *seems* to be much more: the material bodies we know through sensory experience

do much more than occupy space; in addition to this mathematical property they have many physical properties such as colour, smell, taste, hardness, softness, brittleness, etc. But all these words merely denote sensations, reactions of the human mind to the presence of or contact with spatial elements. Such reactions are purely subjective and therefore not capable of undergoing scientific examination. Apart from the geometric characteristics of bodies – size and shape – there are no other suitable subjects for physical investigation than their kinematic magnitudes which determine their conditions of motion with respect to each other. Natural science is therefore solely concerned with these 'primary' qualities and not at all with the 'secondary' qualities referred to above. Strictly speaking, physical bodies only possess primary properties.

Physics therefore is the doctrine of moving spatial forms, an extension of the doctrine of resting spatial forms, i.e. geometry. Like geometry, it should therefore be deducible from *a priori* axioms. In addition to mathematics, the human mind also produces physics. It would be better to say that it produces various forms of physics, for whereas mathematical axioms irresistibly force themselves upon everybody in the same way in respect of shape and motion of spatial elements, numerous possibilities are conceivable corresponding to various material worlds.

Experience, or empirical investigation, is the only means of determining which of all these possibilities is actually realized in nature. Descartes here finds the link with the new experimental trend of science with which he seemed at first to be entirely out of contact.

Descartes therefore did not conceive his picture of the universe entirely independently. It might be said that it ultimately came into being by the same combination of Galileo's *metodo risolutivo* and *metodo compositivo*, except that the first method was shortened to the point of being unrecognizable. No experience of the senses is required to find the formulation of the hypotheses used as starting points for deductions in the second part of the procedure.

No detailed account can be given here of the manner in which

Descartes put his principles into practice, but it will be discussed in broad outline.

The identity of matter and space immediately leads to some important conclusions: (i) the world is extended infinitely; (ii) it consists of the same matter throughout; (iii) matter is infinitely divisible; (iv) a vacuum, i.e. a space not containing any matter, is logically contradictory and thus impossible.

The first question suggesting itself is how the differentiation into different bodies observed in the world has been achieved. Although space can be imagined to be divided into parts by surfaces, these parts are not therefore separated from each other. Separation is brought about when they start moving with respect to each other while maintaining their shape. Joint motion or joint rest proves to be the differentiating principle causing the coherence of spatial elements and their differentiation. It is to be imagined that God, when creating the world, divided space into parts of various shapes and sizes and then set these various parts into a wide variety of motions in respect of each other. This actually took place. A clearer picture will, however, be obtained if the world is not conceived as having been created at once but as having gradually developed into its present shape. This makes it possible to understand that three orders of magnitude of spatial elements came into being: the particles originally present partly ground each other down to small spheres, partly conglomerated to coarser items of matter through the binder of mutual rest. The pieces formed during the former process consist of extremely fine particles which move at high speeds and fill up all the interspaces between the parts of the two other items of matter. (This is how one is naturally inclined to represent the conception; in reality, of course, these interspaces *are* the pieces.)

When all this has been achieved (properly speaking from the outset) the situation is as follows: the spherical particles of the so-called second matter form large vortices which, owing to their centrifugal tendency, force these extremely fine, primary particles, or particles of subtle matter, to the centre. They form spherical conglomerates there: the sun and the fixed stars. Each

of these therefore has a vortex or sky of secondary particles around it, which are therefore also called celestial particles. The coarser tertiary particles form the earth and the planets, the interspaces of which are filled up with secondary particles which in their own interspaces contain subtle matter and are also comprised under the general term of celestial matter. The quantity of matter of an earthly body (which for the sake of convenience we shall call by its modern name of mass) is assessed from the total volume of tertiary particles contained in it. This volume is equal to the volume observed empirically, decreased by the sum of the volumes of interspaces filled up with celestial matter.

All changes taking place in nature consist of motions of the three types of spatial elements. The primary cause of these motions is God's *concursus ordinarius* (common concourse), the continuous act of maintainance. He conducts all motions in such a way that the total momentum, i.e. the sum of all products of mass and speed, remains constant. This relation: $\Sigma\ mv =$ constant, constitutes the supreme law of nature. It results from God's immutability, in the sense that, although He wished to let the world be in motion, change should yet be as immutable as possible.

The supreme law, however, by no means determines the course of natural events. There are three other laws acting as secondary guiding principles. The general idea underlying the first law is that nothing changes in the spatial or material elements without an external cause: shape and size of a body, the condition of being or not being united with other bodies in common rest or separated from them by relative motion, the condition of rest or motion itself – none of this ever changes spontaneously, from internal causes, but only through the action of other bodies. Each body therefore has a certain individuality and solidity clearly distinguishing it from ideal geometric forms. The second law contains the principle of inertia: the tendency to maintain motion assumed in the first law is now further defined as an endeavour to continue at any instant rectilinearly at the speed then attained, irrespective of the nature of the motion.

Although all motion must consist in a circular course of bodies (space being full), the third law nevertheless deals with the case of a collision between two bodies without reference being made to the consequences for the surroundings. This being the only way in which a body can act upon another (or rather seems to act upon it, for in fact all motions are effected and conducted by God), this law contains the essential basis of Cartesian physics. It again starts from the tendency to persist in rest or motion assumed in the first law, this tendency now being described as a force capable of resisting disturbance of rest or of continuation in a straight line. This tendency to persist is dependent on the *quantitas materiae*, i.e. mass. According to the third law, a moving body cannot set in motion a body with a larger mass that is at rest. Since, however, total momentum cannot change, the first body itself continues in another direction at its original speed. If, on the other hand, it has a larger mass than the body at rest, it overcomes the latter's tendency to rest and carries it along, losing thereby as much momentum as it imparts to the other body. Christiaan Huygens afterwards pointed out the fundamental error implied in these laws of collision. In a collision of bodies the total momentum indeed remains constant, but only if momentum is considered as a vector.

An important place in the Cartesian picture of the universe is occupied by the vortices of celestial matter round the sun and the fixed stars. The vortex around the sun carries the planets along in the same way as pieces of wood can be seen turning in a whirl of water. The particles of the whirling celestial matter, of course, all possess the centrifugal force revealed by a pressure on the layers further out which *in instanti* is propagated throughout space. This pressure is observed as the light emitted by sun and stars; this emission should not, however, be understood to be an activity of these bodies, but only implies that light is caused by the whirl of celestial bodies around them.

We shall not follow Descartes further in his highly detailed description of the origin of the position of the various vortices with respect to each other, of the way in which they revolve without hindering each other, of the complicated motions by

which the subtle matter is exchanged from one vortex to the other, and of the origin of planets. Nor shall we dwell on the equally detailed treatment, based on his remarkable imagination, of the wide variety of physical and chemical terrestrial phenomena, all of which explain with no other assumptions than those concerning the shape, size, and motion of particles of matter.

One exception should, however, be made: the phenomena explained as the effect of motion include gravity. This constitutes a change that is of essential importance. With a few isolated exceptions, gravity had till then been conceived as part of the essence of a body, usually as an internal tendency, either to reach its natural place or to be united with a larger, similar body. This conception was now suddenly changed: a spatial element in itself only has shape, size, and motion, none of which properties implies any urge to move in a certain direction or to combine to one entity; if, nevertheless, there seems to be such an urge, it must be accounted for by external influences. This is again done by means of the celestial matter which also forms a vortex round the earth, thus carrying it along in daily rotation. This matter tries to escape tangentially, which results in a radial centrifugal force with respect to the revolving earth.

When a stone, which contains comparatively little celestial matter and therefore has a great density, is released in the air, which contains a fairly large quantity of celestial matter and thus has little density, the centrifugal tendency of the celestial matter can be satisfied when the denser body is replaced by a quantity of air that is lying lower. Therefore the body moves downwards; when held in the hand, this urge of the celestial matter is experienced as gravity.

Now that the Cartesian system has been sketched in broad outline, we should briefly revert to what has been said above in respect to its mathematical nature. It will have become clear that this should not be understood to mean that Descartes expressed the reasoning by which he explained natural phenomena in mathematical formulae. On the contrary, nowhere did he give a mathematical argument and he was invariably very vague in

expressing functional dependences. In the solar vortex, both the period of revolution of the celestial particles and their size increase with increasing distance from the sun, but we are not informed of the mathematical relation of these increases and no attempt is made even to determine the relation between the period of revolution of a planet, its density, and its distance from the sun. The mathematical content lies in the axiomatic structure of the whole, in the postulation of incontestable fundamentals, and in the deductive treatment of the phenomena. It will be seen that it is not until Huygens that full justice is done to a mathematical treatment by means of formulae.

Cartesian physics is usually referred to as being mechanistic, meaning that it uses no other principles of explanation than conceptions dealt with in mechanics (geometric conceptions such as form and size occur in mechanics too because it is a sub-division of mathematics) and motion is its specific subject. Cartesianism only recognizes what can be described and explained by means of these conceptions as actually existing in nature.

In addition to the primary meaning of the word mechanistic, i.e. 'with the aid of mechanics', Descartes attached a secondary meaning which was afterwards often given to it exclusively, namely that of a tool that can be imitated in a mechanical model.

He expressly stated that he recognized no other difference between natural bodies and products of human workmanship than that of dimension: what occurs in the former takes place also in the latter, but on such a large scale that we can see it. For the rest, there is not a single difference between a going timepiece and a growing tree. For this reason those who are skilful in making automata are the most suitable persons to detect the true facts of natural phenomena, because this means guessing at the mechanism behind them. Descartes thus pronounced a principle of explaining nature which was to govern physics for a very long time, namely that explanations should primarily be capable of being demonstrated; it should be possible for a skilful craftsman to imitate natural phenomena in a model.

The above may contribute to eliminating the seeming contradiction between the a-prioristic-deductive manner in which Descartes wished to study natural science and the keen interest he always showed in empirical investigation and technique.

This contradiction had already partly been eliminated by what has been observed above about the function which he assigns to experiment for establishing the agreement between a deductively constructed world of ideas and physical reality. It is now further reduced by his assertion that the handling of tools creates a favourable disposition to fathom the hidden actions of nature. It disappears altogether when we take into account the high expectations entertained by him regarding the social importance of scientifically based technique for the future human community. This, and not any agreement in philosophy, constitutes the basis of his affinity with Bacon and of his appreciation of him. He could not possibly have shared the English philosopher's views on the method of investigating nature. But he probably never knew these views.

In the final chapter of the *Discours* Descartes gave a detailed description of all the blessings he expects of the future development of natural science. It will make us *maîtres et possesseurs de la nature* (masters and proprietors of nature). This will enable us not only to benefit more from the fruits of the earth and all the good things it offers us, but also to protect and preserve health, which is the greatest good of all.

Descartes was always greatly interested in medical science. With the exception of the enigmatic interaction with the soul (a subject which he dismissed rather lightly) the living human body is to him a machine the operation of which can be understood by means of mechanics. (The bodies of animals, which have no soul, is no more than that; they have no consciousness and, contrary to appearances, they possess no feeling.) Medical science is concerned with remedying disturbances in the mechanism of the body. As this implies knowledge of the arrangement and the operation of this mechanism, medical science requires the study of physiology in addition to mechanistic physics and chemistry. This view, which was to find its natural expansion

in the later conception of a living body as a physico–chemical process, has greatly affected medical thought.

Descartes' high appreciation of medical science is clearly reflected in the famous picture he drew of the interconnexion between the various sciences: *Toute la philosophie est comme un arbre, dont les racines sont la Métaphysique, le tronc est la Physique, et les branches qui sortent de ce tronc sont toutes les autres sciences, qui se réduisent à trois principales, à savoir la Médecine, la Mécanique, et la Morale.* We shall not enter into the question of how morals are connected with physics.

After giving this general impression of the Cartesian philosophy of nature we shall briefly discuss some of his concrete contributions to physics. The most important were in the field of optics where he stimulated development very strongly.

In *La Dioptrique*, one of the three *Essays* appended to his *Discours de la méthode*, he gave a theoretical deduction of the sine law of the refraction of light, which the Dutch mathematician Willebrord Snellius (1591–1626) had found experimentally. We cannot be certain whether Descartes knew this result.

Had he remained true to his principles he would have started his deduction from a philosophical theory of the nature of light. Instead he compares a ray of light passing through a flat boundary plane into a denser medium with a bullet striking the boundary plane of a permeable medium obliquely with a large velocity v_1. He assumed (Fig. 16) that the velocity is increased at a certain ratio to v_2, and that its component along the boundary plane is not changed. He then proved that if the angles of incidence and refraction of the ray of light (or the bullet) with the vertical are i_1 and i_2 respectively the relation:

$$\frac{\sin i_1}{\sin i_2} = \frac{v_2}{v_1}$$

holds, thus not only finding the Snell's law of refraction:

$$\frac{\sin i_1}{\sin i_2} = n_{1,2}$$

but also the relation between the refractive index and the velocities of light in the two media:

$$n_{1,2} = \frac{v_2}{v_1}$$

which, as we shall see, was believed to be true by many physicists up to the beginning of the nineteenth century. We shall from now on describe the third equation as the Descartes relation.

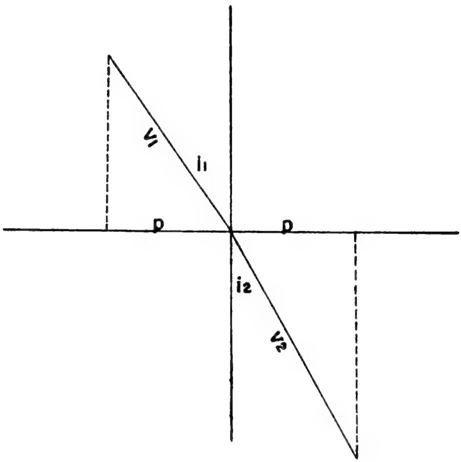


Fig. 16. Descartes' deduction of the law of refraction.

Apart from the comparison used in this deduction between a ray of light and the trajectory of a projectile, Descartes in his *La Dioptique* gave two further pictures which allow one to form a graphic conception of light. In the first place, sight is compared with the way in which a blind man has to feel his way with the help of a stick. A second picture, the so-called wine-vat picture, compares light passing through a transparent body with the flow of wine from holes in the bottom of a vat filled with pressed grapes. All three concepts were repeatedly applied during the seventeenth century.

In the same *Essay* extensive theories were also developed with respect to the action of the eye, the improvement of sight by means of lenses or composite optical instruments, and the technique of grinding lenses.

In *Les Météores* Descartes developed a theory of the rainbow in which, proceeding along the line indicated by Dietrich von Freiburg in the thirteenth century and followed by Marcus Antonius de Dominis (1566–1624) in the sixteenth century, he explained the primary rainbow as the result of two refractions and one reflection, while he also deduced mathematically that half the vertical angle of the cone formed by the rainbow and the eye as its vertex is 42°. For the secondary rainbow, which is the effect of two refractions and two reflections, he found in the same manner an angle of 52°. He dealt at length with the origin of colours but, as nothing was known at that time about the relation between colour and refractive index we need not wonder that his speculations did not result in any conclusion of lasting value. A typical characteristic of his theory is the fact that he ascribed differences in colour to rotating velocities of corpuscules. The particles rotating most rapidly give the sensation 'red', as the velocity decreases the colour shifts via yellow to green and blue. This idea found favour with many seventeenth-century scientists.

Further contributions to optics were made in *La Dioptrique* and in *La Géométrie* by investigations of elliptic and hyperbolic refractive surfaces and by theoretical discussions of a Goliath microscope with a parabolic mirror for illumination.

MARIN MERSENNE (1586–1648)

The name of Marin Mersenne, a French Minorite, is inseparably associated with that of Descartes. He was Descartes' most faithful correspondent, making and maintaining his principal contacts with other scientific workers. He did this for many of his contemporaries and his historical importance is mainly based on this function. In a time which knew neither scientific periodicals nor congresses, correspondence was practically the only means

of communication between scholars. The scientific life of the seventeen thirties and forties was highly stimulated and promoted by the centre constituted by Mersenne's austere monastery cell in the Place Royale (now Place des Vosges), Paris.

The importance of this work sometimes makes us overlook Mersenne's own contributions to science. Not only did his philosophical and theological treatises stimulate emancipation from the Aristotelian system and prove its compatibility with the Christian doctrine; he also definitely contributed to its further development, chiefly in the field of acoustics. The empirical laws regarding the relations between tension, length, and thickness of a vibrating string to the pitch of the tone produced are still rightly called after him. Of the works which he devoted to acoustics, special mention should be made of his *Harmonie universelle* (1636–7).

PIERRE GASSEND (1592–1655)

The last important figure of the Age of Descartes to be discussed is the French priest and scientist Pierre Gassend or Gassendi. He deserves credit for restoring antique atomism to its former glory, thus opening up new paths to natural science. He argued in various publications that the atomism of Democritus, Epicurus, and Lucretius (95–55 B.C.), which throughout the Middle Ages had been in disrepute on account of its close relationship to atheism and had seemed unacceptable to Christian thinkers, was essentially compatible with Christian doctrine. He demonstrated its use in explaining numerous physical and chemical phenomena. With an ingenuity in no way inferior to that of Descartes, he managed to explain literally the whole of nature by assumptions as to shape, size, position, arrangement, and motion of atoms. The fact that these explanations sound extremely naïve to a modern reader and that Gassend often thought he understood a situation which constitutes a problem in the *macro*-world by considering it to be self-evident in the *micro*-world, should not lead us to underestimate the stimulating effect created by his atomistic views.

Although Gassend's theory of matter differed in many essential points from Descartes' (his assumption of atoms was as little in keeping with the Cartesian system as the void in which they moved), during the later development of physics both their views were often referred to under the common name of corpuscular philosophy and applied indiscriminately. This is not unnatural. Although, on the strength of the identity of space and matter, Descartes was forced to assume the infinite divisibility of the latter which had of old been assigned to the former, this does not mean that man should be capable of actually effecting the imagined, infinitely continued division of matter. Particles, however, which are divisible in the imagination but not in reality show exactly the same behaviour as Democritean atoms (which can also be divided in the imagination). Moreover, a space containing exclusively celestial matter offers no resistance to the motion of a tertiary particle and is thus indistinguishable from vacuum.

A rising generation of physicists and chemists who saw in the corpuscular theory possibilities of advancement in their special branch were not in the least troubled by the fact that in the identification of Cartesian with Gassendistic views a great many subtle differences were overlooked (the two thinkers themselves would certainly have protested). In the seventeenth century English investigators of nature in particular had no scruples in making a liberal use of corpuscular hypotheses without worrying whether they came from Descartes or from Gassend. There was, of course, also another source: the theory of the *minima naturalia* discussed in Chapter 2 (p. 38). Atomistic influences have sometimes been too readily assumed in authors expressing corpuscular views because this possibility was overlooked.

CHAPTER 12

Physics in the Seventeenth Century (3) *The Age of Huygens*

IN the preceding chapter we have seen how a general philosophica and methodical framework for the study of natural science was created by the activities of such thinkers as Bacon, Descartes, and Gassend. This framework, however, needed filling up with definite empirical and mathematical data before any real progress could be spoken of. This task was to a great extent fulfilled by the men discussed in this chapter.

BLAISE PASCAL (1623–62)

Blaise Pascal, one of the great figures of cultural history, placed only a small part of his eminent gifts at the service of natural science, so that he presents a highly incomplete picture if he is viewed as a physicist only. The scope of this book does not permit us to devote attention to the other aspects of Pascal, his penetrative work as a mathematician, the brilliant polemic talents developed in his controversy with the Jesuits, his deeply felt and highly personal religious views, and the literary gifts with which he was endowed. His posthumous sketches and drafts for an apology of the Christian religion, which under the title of *Pensées* are still being read in many languages, are among the great monuments of French literature.

His work as a physicist originated in the news which reached France in 1646 of Torricelli's barometric experiment of 1643 and its explanation by means of the idea of atmospheric pressure. He immediately set himself the task of repeating this experiment under varied conditions to verify the suggested explanation. He completed this task in the years 1646 to 1648. In 1648 his investigation culminated in the experiment on the Puy de Dôme, which

confirmed the inference from the theory of atmospheric pressure that the mercury column in Torricelli's tube would be shorter on the top of a mountain than at its foot.

It is always difficult for a modern reader, who has learnt all this as a child, rightly to assess the value of Pascal's investigation and to see that it is just as much an essential feature of his character as his mathematical discoveries about the cycloid, his *Lettres provinciales*, and his *Pensées*. No one can duly appreciate this work unless he fully adapts himself to the thought of Pascal's time, knows the other explanations then current of the barometric phenomenon, and realizes that the result of his experiment on the mountain was by no means a foregone conclusion for contemporary physicists. Only then can one form an idea of the perspicuity with which Pascal successively disproved all objections to the theory of atmospheric pressure, systematically eliminated all current erroneous views, and verified all the inferences to be drawn from this theory.

After laying the foundations of aerostatics he combined this with hydrostatics to form one single subject: statics of the fluid state, which is fully described in his posthumous work *Traités de l'équilibre des liqueurs et de la pesanteur de la masse de l'air* (1663). Together with the *Récit de la grande expérience de l'équilibre des liqueurs* (1648) it is one of the classics of scientific historical literature.

All Pascal's physical investigations reflect his extremely strict conception of the hypothetico-deductive method applied by him. Before a hypothesis had been empirically verified, he refused to regard it as anything but *une vision, une caprice, une fantaisie*, at best as *une belle idée*. This accounts for his scepticism as regards Descartes' fantastic explanations of nature – although in principle he accepted the latter's mechanistic conception of nature – and his highly reserved attitude in the controversy about the world systems of Ptolemy, Copernicus, and Tycho Brahe, an attitude which is surprising only to those who have only a superficial knowledge of his mode of thought. These systems were to him three hypotheses of equal value, from which he could make a selection only on the strength of new facts. This same strict con-

ception gave rise to the scourging reproaches he lashed at the Jesuits in the eighteenth *Lettre provinciale* for their share in Galileo's condemnation.

EXPERIMENTAL PHYSICS IN THE SEVENTEENTH CENTURY

Through Pascal the barometer had made its appearance in the cabinet of physical instruments, to which early in the seventeenth century the telescope had been added and which was soon to be enriched by the compound microscope. The next important acquisition was the air suction pump. Its invention by Otto Gericke (later Von Guericke) at Magdeburg was published in 1657 in Kaspar Schott S.J.'s *Mechanica hydraulica–pneumatica*, while its design and applications were dealt with in detail in Von Guericke's own work *Experimenta nova (ut vocantur) magdeburgica de vacuo spatio* (1672). He put his invention to various uses, including a water barometer over ten metres high, by means of which the first comparative atmospheric pressure measurements were made in Germany; the Magdeburg air-gun (operated by partial vacuum); and the sensational demonstration of the Magdeburg hemispheres which, incidentally, does not seem to have been given in the Diet of Ratisbon in 1654, but later, in 1657.

Von Guericke's investigations were not confined to pneumatics. He designed an electric machine in which static electricity was generated by the friction of a rotating ball of sulphur, and he was also engaged in cosmological problems.

The information about Von Guericke's air pump in Schott's work stimulated the British scholar Robert Boyle (1627–91) to design a similar instrument. He did so with the assistance of the young Robert Hooke, who later on was to make a great name as an experimenter as Curator of Experiments of the Royal Society. During the next few years Boyle used his pump in a large number of experiments on air pressure and the phenomena in rarefied air.

These experiments were dealt with at length in his *New Experi-*

ments Physico-Mechanical touching the Spring of the Air and its Effects (1660). As the title shows the principal subject discussed in this work is what was then called the elasticity (ἐλατήρ, spring) of the air, in particular its capacity to expand upon reduction of external pressure. It should be observed that in those days there was no question of an explanation of the tension of a gas as the effect of collisions of moving molecules against the walls of a vessel. Boyle discussed two other concepts: according to one, elasticity is attributed to particles of the gas itself; according to the other, it is derived in the Cartesian manner from the motion of celestial matter.

The elasticity of the air was treated quantitatively for the first time in Boyle's *A Defence of the Doctrine touching the Spring and Weight of the Air*, in which he reacted to critical comments on his air-pressure experiments. To put an end to doubt that had been expressed as to whether the weight and the elasticity of the air would be great enough to bear the column of mercury in the Torricellian tube, Boyle showed that the quantity of air in the short sealed leg of a U-tube, the other leg of which is long and open, can balance much higher columns of mercury in the open leg.

One of his correspondents, Richard Townley (second half seventeenth century), suggested that the volume and the tension of the enclosed air might be inversely proportional to each other. Boyle confirmed this surmise by an experiment and then showed with a tube in a deep mercury reservoir that the same ratio also applied to tensions lower than one atmosphere. Thus he discovered the law which still bears his name, the first quantitative law of nature outside the range of phenomena of motion, and as such of great historical importance.

In describing one of his experiments Boyle observed that the tension of an enclosed volume of air is increased by heating. He paid no further attention to this phenomenon and even less did he examine it quantitatively. It would seem that he did not attach much value to the quantitative aspect of pneumatic phenomena, quantitative natural science having made only little headway in his time.

Boyle has only been dealt with as a physicist here. His importance for the development of chemistry will be discussed in Chapter 13.

We cannot enter into his interesting treatises on the relation between the Christian religion and natural science, which was a burning question in his time. His opinion, which deviated from the tendency that was gaining ground, is unmistakable from the title of one of his works which, as was customary in those days, is also a brief table of contents: *The Christian Virtuoso*: shewing that by being addicted to Experimental Philosophy a man is rather assisted than indisposed to be a good Christian.*

Robert Boyle is certainly the central figure of England's highly flourishing experimental science in the seventeenth century. Bacon's appeal for a combined study of natural science and technique had produced its effect. Impulses in the same direction also came from other quarters. From before 1600 there had been an endeavour to achieve a synthesis between the theoretical science of the scholars and the practical knowledge of artisans, instrument makers, sailors, etc. The universities of Oxford and Cambridge, however, failed to meet the desire for mathematical and scientific instruction in combination with practice. Private enterprise was stirred and induced such persons as Sir Henry Savile (1549–1622) to found the Savilian professorships of geometry and astronomy, which over the centuries have been held by various illustrious scholars. On the initiative of the Privy Council, and with the support of merchants, a lectureship in mathematics was established in London in 1588 and entrusted to Thomas Hood. In addition to mathematics he taught astronomy, geodesy, and navigation. This last subject was in great demand in seafaring nations in connexion with the great expansion of shipping. In England this need was met by Hood and his colleagues and also by Edward Wright in his work *Certaine Errors in Navigation Detected and Corrected* (1599); in Portugal by Pedro Nunes (Latin: Nonius; Spanish: Nuñez, 1502–78); and in the Netherlands by Simon Stevin (1548–1620) and Petrus Plancius (1551–

* A term current in the seventeenth century for an experimental philosopher.

1622). A strong influence in this direction was also exerted by Gresham College, established in London in 1575 by Sir Thomas Gresham, but which did not commence work until 1598. It has sometimes been called England's third University. The seven chairs included physics, geometry, and astronomy, so that mathematical and physical subjects were adequately represented. The lectures, which were intended for the citizens of London, were given by professors who were in contact with navigators and shipbuilders. The meetings of scientifically minded persons at Gresham College greatly promoted scientific pursuits in England in the seventeenth century.

Other similar scientific centres were formed, for instance the 'Invisible College' at Oxford under the direction of John Wilkins (1614–72), Warden of Wadham College, and with great scholars such as Sir Christopher Wren (1632–1723), Thomas Sydenham (1624–89), and Robert Boyle as its members.

After the Restoration the Royal Society was created from these various groups and received its charter from Charles II in 1662. Its principle was the Baconian-empirical view reflected in its device: *Nullius in verba* (short for *nullius addictus iurare in verba magistri*, Horace, Epist. I, i, 14, meaning: *nulli magistro ita addictus ut in eius verba iurarem* – not devoted to any master to such an extent that I would swear to his words).

The Royal Society, which from 1663 had Robert Hooke's talent for experimenting at its disposal, carried out important work with his aid. It was prepared to test all assertions and surmises, including some that would not be considered worth the trouble of verification in our time.

The establishment of the Royal Society had been preceded in Italy by that of the Accademia del Cimento at Florence by the two brothers the Grand Duke Ferdinand II (1610–70) and the later Cardinal Leopold de' Medici (d. 1675). In 1666 it was followed by the institution of the Académie des Sciences in Paris, where Jean Baptiste Colbert (1619–83), Louis XIV's Minister, assembled various important scholars from France and abroad.

The Cimento existed only till 1667. The Royal Society and the Académie des Sciences, however, expanded to become institutions

of eminent importance for the development of science. It was not until the nineteenth century that they and the institutions organized after their example in other countries were outstripped by the universities.

Before turning to the central figure after whom this chapter was named we must first discuss two works of great importance for seventeenth-century optics which were published almost simultaneously, namely *Physico-Mathesis de lumine, coloribus et iride* (*Physical Mathematics of Light, Colours, and the Rainbow*, 1665) by the Bolognese priest Francesco Maria Grimaldi and *Micrographia or some Physiological Descriptions of Minute Bodies by Magnifying Glasses* (1665) by the above-mentioned experimenter Robert Hooke.

Grimaldi's very elaborate work forms a precious source of knowledge of seventeenth-century optics and it derives its lasting historical value from the fact that here for the first time phenomena of the diffraction of light are discussed. The word was introduced by the author himself to denote what he considered to be the fourth form of the propagation of light besides direct transmission, reflection, and refraction. Grimaldi described two groups of experiments: in the first a screen with a small opening is placed in the way of a beam of light and the transmitted beam is thrown on to a white screen. The phenomena observed are minutely described but evidently the author was not yet in a position to explain them plausibly. In the second group of experiments a beam of light originating from a very small opening meets a small obstacle and its shadow on a screen is investigated.

In the further course of his work he investigated all the main problems of contemporary optics: first of all whether light is a *substance* (a thing existing on its own) or an *accidens* (a property of something else). He was inclined to believe it to be a very finely divided, quickly moving subtile fluidum, but he appreciated the objections against this theory as well as the arguments which seem to point to an 'accidens' theory. He also discussed different explanations of reflection and refraction and the still totally unrevealed relation between light and colour.

Hooke's *Micrographia* is primarily important for the development of the microscope and microscopic observation. It contains the earliest description of a compound microscope with special apparatus for the illumination of opaque objects and it shows various illustrations which were the result of very careful observations. In addition, it describes a systematic investigation of the circumstances under which colours occur in thin sheets and a theory of light and colours.

Hooke proposed an undulatory theory on the nature of light. Though he did not attain results of lasting value, he certainly helped in establishing clearer ideas about optics and he counterbalanced a trend in favour of the corpuscular nature of light. Speaking of Hooke, we cannot ignore his share in the development of the theory of elasticity. He formulated the law which still bears his name: *Ut tensio, sic vis* (elongation is proportional to the force producing it).

Among others who discussed the many unsolved problems of optics, were the above-mentioned Marcus Antonius de Dominis, the Bohemian scientist Johannes Marcus Marci de Kronland, who in 1648 published a work, *Thaumantias*, dealing with the rainbow and the colours, and the Dutchman Isaac Vossius who published his *De lucis natura et proprietate* (*On the Nature and Properties of Light*) in 1662.

An entirely new treatment of refraction was applied by the French mathematician Pierre de Fermat (1601–65). With the help of calculus, one of the foundations of which he had helped to establish in his theory of maxima and minima, he demonstrated (Fig. 17) that when a ray of light from point A in medium I after refracting on the boundary plane with medium II in C reaches a point B in medium II, the time needed to proceed from A to B via the boundary plane is a minimum. Hence no causal explanation of the phenomenon is attempted here but the difference between the real path ACB and an imaginary one AC_1B is made understandable by making the classical assumption that Nature in a certain sense established its effect in the simplest way.

For his derivation Fermat of course needed a supposition about

the ratio of the velocities v_1 and v_2 of light in the media I and II. Diametrically opposed to Descartes he assumed that

$$\frac{v_1}{v_2} = n_{1,\,2}$$

which expression we will designate as Fermat's relation.

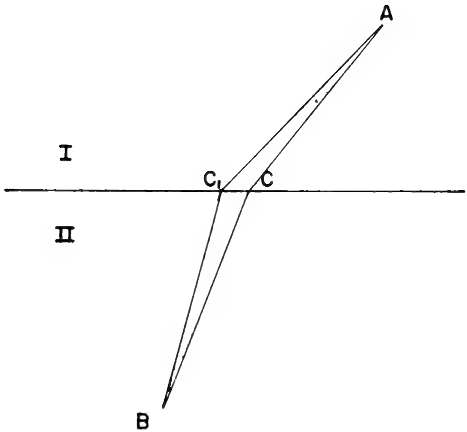


Fig. 17. Fermat's principle of least time.

CHRISTIAAN HUYGENS (1629–95)

Among the scholars invited by Colbert to come to Paris as members of the Académie was the Dutchman Christiaan Huygens, the only foreign member. After devoting himself to purely mathematical problems as a follower of Archimedes, and thus acquiring European fame, in the sixteen-fifties Huygens became more interested in natural and applied science, for which his great mathematical gifts stood him in good stead. With the assistance of his brother Constantijn, he ground his own lenses and combined them to form telescopes with which he made astronomical discoveries. He was the first to observe, in 1655, a satellite of Saturn, now called Titan, and he interpreted the special

feature in the appearance of the planet itself, which had already been noticed by Galileo, as a ring surrounding it. Between 1655 and 1658 he designed his pendulum clock in which the clockwork was regulated by a pendulum. This marked the beginning of a new epoch in the history of clockmaking. Later on he made widespread theoretical as well as practical investigations in the fields of science and engineering.

In designing the pendulum clock, Huygens had from the outset been motivated by the wish to contribute to the determination of longitude at sea, a problem which was urgent for all seafaring nations. It had been known for a long time that all that was required was the determination of the difference between local time and the time of a zero meridian. However, to this end it was necessary to have this 'zero time' on board the vessel, as it were, so that a clock was required which would show it. Huygens at first tried to use the pendulum clock for this purpose. When this did not prove successful, he developed a large number of variants of his original clock till at length he found the balance wheel operating in conjunction with a helical spring, which has been used in horology ever since. This invention is also attributed to Hooke.

The study of the theory of the pendulum clock led in the first place to the demand for a pendulum oscillating exactly isochronously, and not approximately isochronously as did the single pendulum. The solution he found for this problem was that the point of oscillation should not describe an arc of a circle but of a cycloid. This could be effected by making the suspension wire moved between two cycloidal cheeks. He found this out by first developing the theory of evolvents of curved lines, showing that the evolvent of a cycloid is a cycloid congruent to it.

As a real pendulum does not consist of a material point suspended from a mathematical thread, but of an actual physical body revolving on a horizontal axis, he set about studying the physical pendulum, thus making the first step towards the dynamics of solid bodies. He learnt how to determine the length of a mathematical pendulum in isochronous oscillation with a given physical pendulum, for which purpose he had to introduce the

concept of moment of inertia. One of his other discoveries was the fundamental proposition of the interchangeability of point-of-suspension and point-of-oscillation of a physical pendulum.

Both the pendulum clock itself and the various theoretical investigations based on it are dealt with in the work *Horologium oscillatorium* (1673), not to be confounded with his *Horologium* (1658) in which he had given the first account of the pendulum clock.

In addition to the practice of grinding lenses and the manufacture of telescopes and microscopes, the theory of lenses and optical instruments held Huygens' interest throughout his life. He devoted special attention to spherical aberration. To reduce this error to a minimum he designed telescopes having an object lens of a very large focal length, as a result of which the telescopes became so long that it was practically impossible to place the object and eyepiece in a tube. This inspired him to make his so-called air telescope, the object lens of which was fastened to a high post, the observer holding the eyepiece in his hand.

He also made microscopic biological investigations, but in this respect he was surpassed by his younger contemporary Antonie van Leeuwenhoek who, owing to his exceptional power of observation became the actual founder of microbiology. It should be mentioned that Leeuwenhoek did not use compound microscopes but made his observations exclusively through small lenses which he ground himself.

In his *Traité de la lumière* (1690) Huygens developed a mechanistic theory of light which was an important contribution to physical optics. In this work he conceives light as a propagation of impulses in a subtle medium, by means of which he explains the phenomena of reflection and refraction in a manner that has since become classical. There he finds for the relation of the velocities of light v_1 and v_2 in two media 1 and 2 $\frac{v_1}{v_2} = n_{1,2}$, i.e. Fermat's relation. Moreover, by assuming two wave fronts advancing at different velocities, he succeeds in completely unravelling the phenomenon of double refraction in calc-spar describing in 1669 by the Dane, Erasmus Bartholinus, in his work

Experimenta crystalli islandici disdiaclastici (*Experiments on the Double Refractive Icelandic Crystal*). His method of treatment is still used in modern textbooks on physics. A permanent place in natural science has also been given to Huygens' principle that when a disturbance is propagated in the ether each particle affected by it becomes the source of a new disturbance extending to all sides.

Attention should be drawn to the fact that Huygens' theory of light is a pulse theory and not a vibration theory. He stated emphatically that the pulses imparted by the particles of a luminous body to adjacent ether particles are not periodic. Accordingly any concepts such as wave-length and frequency are out of the question. There is no objection to his theory being called an undulation theory provided that no propagation of vibrations is assumed.

It will now also be clear why some of Huygens' observations remained to him isolated and incomprehensible cases, such as a special property acquired by a beam of light after passing through a double-refractive crystal, afterwards to be interpreted as a polarization phenomenon. This is not because he considered the vibrations of light to be longitudinal, but because to him there were no vibrations at all. This may also account for the remarkable fact that he took no notice of the discovery of diffraction by Grimaldi, though we know that he possessed his book.

The above may have given an impression of the interplay between theory and practice which is so characteristic of Huygens and which helped to place Bacon's ideas of the social function of science on a higher scientific level.

In the purely scientific field he did the same for Descartes, who had drawn up a programme of the mechanistic explanation of nature but had not been able to base this explanation on well-founded mathematical theories. This was done for him by Huygens.

The ideas which Descartes had in his mind about light and gravity materialized in Huygens' *Traité de la lumière* and in his *Discours de la cause de la pesanteur* (1690). In *De coronis et parheliis* (1663) meteorological phenomena are treated on the

principles indicated in Descartes' *Les Météores*, but on a much higher level. Descartes' highly disputable collision theory described in the *Principia philosophiae* is refuted and replaced by a better theory in Huygens' *De motu corporum ex percussione*, a work which Huygens wrote in 1656, but which was not published before 1703. In the meantime, the results (but without any proof) had been published in the *Horologium oscillatorium* (1673).

In the latter work, in combination with treatises published in 1668 by John Wallis and by Christopher Wren, the theory of collision is very greatly advanced. But it is also important for the clear formulation of two general principles of mechanics and the applications made of them, namely:

(i) The principle of relativity of classical mechanics, which Galileo had intended for random combined movements of a system of bodies, is here for the first time given the exact form exclusively dealing with a joint rectilinear uniform translation.

(ii) Torricelli's axiom is now generalized to the following dynamic postulate: when in a system of connected bodies each body is at a given moment allowed to use its instantaneous velocity to rise vertically, then held at its highest point, and the system's common centre of gravity is determined, the result is a virtual height of centre of gravity which cannot be changed by the mutual actions of the units of the system. This principle is equivalent to the principle of the conservation of energy in the field of gravity of the earth supposed to be homogeneous. In fact, if ther e are n particles with mass m_1 velocity v_1 and height h the virtual height of the centre of gravity is

$$\frac{\dfrac{\Sigma\, m_1 v_1^{\,2}}{2g} + \Sigma\, m_1 h_1}{\Sigma\, m_1}$$

This constant can be expressed as $\Sigma\, \tfrac{1}{2}mv^2 + \Sigma\, mgh = \mathrm{C}$ and is nothing else than the expression for the constancy of mechanical energy.

An important contribution to mechanics is made by the deduction of the centrifugal force acting on a point describing a circle if the motion is regarded with respect to a system of axes revolving with it. This deduction is to be found in *De vi centrifuga*. This

work, like that on percussion, although written in 1659, was not published before 1703. The results were, however, communicated in the *Horologium oscillatorium* of 1673.

THEORY OF PLANETARY MOTION

Since Kepler's time not much progress had been made in the field of theoretical astronomy. His unattained ideal of celestial physics, that of a dynamic explanation of planetary motions, had remained unfulfilled. An attempt to approach it was made by the Italian physician and physicist Giovanni Alfonso Borelli in his work *Theoria mediceorum planetarum ex causis physicis deducta* (1666), containing a theory of a small-scale solar system formed by Jupiter and its satellites. He regarded the motion of a planet as the result of a struggle between a constant centripetal and a variable centrifugal force, but he gave no mathematical formulation or development of this thought (which, therefore, in Pascal's terminology is no more than a caprice or fantasy). Borelli's *De vi percussionis* is of importance for mechanics. His *De motu animalium* (I, 1680; II, 1685), in which a mechanistic physiology is attempted, is a symptom of the advance of the mechanistic view of the world.

To conclude this chapter, mention will be made of two French physicists.

Edmé Mariotte, a priest and physicist who became a member of the Académie des Sciences in 1666, was engaged on various physical phenomena; his work was of special importance for mechanics and hydrostatics. Eighteen years after Boyle he found once more the relation between the pressure and volume of an enclosed quantity of air, so that Boyle's law is more rightly referred to as the law of Boyle and Mariotte. He made the discovery independently; moreover, he seems to have had a better insight into its fundamental significance than his British predecessor. The experimental proof is described in his work *Essai sur la nature de l'air* (1679), in which he tried to found on it a method of barometric determination of heights. The fundamental

physical idea is correct, but he could not work it out on account of mathematical difficulties.

In a work on collision: *Traité de la percussion ou choc des corps* (1677) he describes an apparatus for the experimental verification of laws of collision deduced by Wallis, Wren, and Huygens and records the results of drop tests for determining the resistance of air. His *Traité du movement de l'eau et des autres fluides* (1681), incorporating experience gained during the construction of the large hydraulic works at Versailles and Chantilly, is a contribution to the science of hydrodynamics which had recently been started in Italy by Galileo's pupils Benedetto Castelli and Evangelista Torricelli.

The French physicist and engineer Denis Papin was an assistant of Huygens at Paris and of Boyle in London, in which functions he made improvements in the air pump. As a professor at Marburg he constructed, on the basis of a design for a gun-powder engine by Huygens, one of the earliest piston engines; it is said that he also tried to put it into use for the propulsion of vessels. In various languages his name has remained con-ected with the autoclave.

CHAPTER 13

From Alchemy to Chemistry

A HOST of medieval alchemical manuscripts still linger unpublished in our libraries although catalogues and short descriptions of their contents have become available of late. With the advent of printed books, however, we enter a period in which speculations and discoveries were more readily disseminated among fellow alchemists and those interested in chemical phenomena. Gradually a solid body of chemical data and observations was formed and allowed the transformation of qualitative alchemy into quantitative chemistry by the end of the eighteenth century.

THE LATER ALCHEMISTS

The first printed books on alchemy initiate us into the secrets of the signs, symbols, and terms used by the individual alchemists; they should be studied closely if one wishes to understand such texts, for each author chooses his own terms and a universal 'alchemical language' hardly exists. Moreover, the symbolism is often obscure and, in many cases, beyond our comprehension. These alchemists, seeking to achieve the transmutation of the chemical compounds built up of the four elements, compared their pairs of reacting elements with body and soul, male and female. The union of form and matter as evinced by the colouring of the primary matter was likened to birth, generation, the marriage of Sun and Moon or King and Queen. The creation of the Philosopher's Stone became the 'Chemical Wedding'. Invocations and prayers accompanied the operations, the correct moment of which was calculated from astrological observations, and some of these operations were even indicated by signs of the zodiac.

Amongst the most popular printed alchemical works we find essays of (or often wrongly attributed to) such famous men as Arnald of Villanova (1240–1311) or Raymond Lull (1235–1315).

Such works not only contain speculations but also accurate descriptions of certain chemical experiments, though the lack of pure chemicals often prevented these alchemists from achieving identical results. The alchemical works most remarkable for their contents are probably the books ascribed to one Geber, who was certainly not the Arab alchemist Jâbir ibn Hayyân (ninth century). The most important of these, the 'Sum of perfection', reveals much of the alchemist's mind, but in the words of Dr Holmyard 'the fact that he is attempting the impossible owing to insufficient knowledge and to fundamentally incorrect presuppositions' should not make us overlook the penetration of his mind. He was essentially a forerunner of those modern chemists who set out to synthesize a substance that shall have certain pre-selected properties; he failed only because of lack of proper materials and data.

We have ample knowledge of a number of alchemists like John Dee, Sir Kenelm Digby, Alexander Seton, and Denis Zachaire whose work was known to contemporary society, but also only too often of 'puffers' aiming at monetary gain rather than at better understanding of chemical phenomena. On the other hand we have a host of alchemists and scientists interested in alchemy who seriously tried to establish new chemical facts and to test the theories propounded by others. Among these we find famous names like Boyle and Newton.

PHYSICISTS CRITICIZE ALCHEMICAL DOCTRINES

René Descartes in his *Principia philosophiae* (Amsterdam, 1644) had put forward a systematic corpuscular philosophy, though he aimed at explaining physical phenomena in the first place. Pierre Gassend(i)'s *Philosophiae epicuri syntagma* (*System of Epicurean Philosophy*, Paris, 1649) explained that matter was atomic, the atoms were indivisible particles of the same primary material differing only in shape and size. He also recognized 'moleculae', 'very tiny concretions which, being made by certain types of more perfect and indissoluble coalitions, long endure as the seed of things, which are not atoms, but these can be resolved into atoms'. These and similar corpuscular theories derived from the

atomism of Democritus attacked the reigning Aristotelean theory of the continuity of matter, his doctrine of forms, and his theory of elements and mixtures.

Robert Boyle, though essentially remaining a physicist at heart, attacked the chemical aspects of the Aristotelean doctrines in his *The Sceptical Chymist* (1661) and *The Origin of Forms and Qualities* (1667). He showed by experiment that bodies are not resolved in the same supposed elements 'earth, water, air, and fire' by heat but into widely different and often complex compounds. He expressed doubt whether four elements would be sufficient to take account of these phenomena, but he does not establish a list of such possible elements, nor indicate how one can establish that a body is an element. Nor is the relation between atoms and molecules made very clear, although Boyle maintains that the 'clusters' or groupings of atoms which he recognizes maintain their properties even after chemical reactions. If, therefore, his attacks on the older chemical theories were effective, Boyle did not propound a clear chemical theory in its place.

At the same time Boyle believed in the possibility of the transmutation of elements. He even left evidence of such experiments together with a 'powder of projection' to Locke and Newton, who did not follow it up. Newton himself had studied the books of the ancient alchemists and metallurgists, but he had come to the conclusion that he did not dispose in his laboratory of means of resolving 'particles of the first and second composition' (our nuclei and atoms) without which the transmuting of elements was impossible, though he did not doubt its possibility in principle.

THE HERMETIC PHILOSOPHERS

This criticism of the atomists did little to shake the alchemists' belief in the four elements, spirits, earth, and other entities rampant in medieval alchemy. However, alchemy was fast turning away from the puffer's furnace to religico–mystical speculations on older documents. Since the end of the fifteenth century a new

wave of interest in Neo-Platonic and Gnostic doctrines and the occult Jewish theories of the Cabbala had spread westwards from Italy. Trinity College, the very college where Newton worked, was the centre of such a group, the Cambridge Platonists, between 1670 and 1690. They were particularly interested in the alchemical doctrines and prompted English publishers to collect and print the alchemical classics. Elias Ashmole's (1617–92) famous Theatrum Chemicum Britannicum is probably the most famous of such collections. The new Hermetic Philosophy, which arose from the study of these classics, was purely speculative and was strongly influenced by Roman Catholic and Protestant theology. Analogies of the transmutation of metals with the transubstantiation of the Host, the phases of the life of man, and of marriage abound in these books profusely illustrated with symbolic pictures. It is clear that this movement had little influence on the actual progress of chemical knowledge. It was finally absorbed by the doctrines of the Rosicrucians, the Freemasons, and other speculative humanistic sects of the eighteenth century, having at least saved many older alchemical manuscripts for posterity. Jung has correctly pointed out that modern psychology may help us to understand the symbols, pictures, and allegories of this mystical chemistry. These alchemists revealed their own mentality and the progress of their own soul while conducting their experiments or meditating upon those of others.

HANDMAID OF MEDICINE AND PHARMACY

Attacks also came from an entirely different direction. Philippus Aureolus Theophrastus Bombastus von Hohenheim, better known as Paracelsus, had achieved a miraculous cure for Johannes Froben, the famous Basle publisher and friend of Erasmus. Paracelsus then became lecturer of medicine at the university of Basle, where he taught the doctrines of Galen and violently attacked Aristotle. After a year his abusive language and vicious accusations forced him to resign and wander through Germany and Austria, practising medicine and writing numerous essays before his death in 1541.

To Paracelsus, alchemy was the art of proceeding 'from the impure to the pure'. Hence it was eminently suitable for the manufacture of chemicals for medicinal use. All natural products used up to that date in pharmacy were supposed to contain a valuable 'quintessence' but this was rendered partly impotent by the admixture of much 'dross' which the chemist could remove by extraction, incineration, distillation, and separation. No longer should the doctors rely on herbs based on ancient Greek experience, they should ask the chemist to prepare the necessary 'activity' in a concentrated form before applying it in their medicines. All such biological processes like digestion were to Paracelsus chemical processes, that is chemical substances were transformed into others by the natural evolution which he assumed throughout Nature. All living and apparently dead matter was activated and guided by spiritual beings influenced by the heavenly bodies.

Much of this theory is found in the books of Raymond Lull and his school, but Paracelsus introduced many features of his own. Thus he rejected the four elements of the Aristoteleans and substituted for them three of his own: 'Sulphur', the principle of colour and combustibility, 'Mercury', the principle of liquidity, and 'Salt', the principle of incorruptibility and consistency. These Tria Prima could not be separated from nature in fact, but they preserved their identity in chemical compounds and conferred on them certain characteristics. This three-principles theory was later modified into a five-principles theory (phlegm, mercury, sulphur, salt, and earth) by Paracelsus's followers, but it had the same inherent vices of the Aristotelean theory, and was doomed to failure.

However, Peracelsus gave stimulus to a tendency, already present in an earlier generation of alchemists, to examine carefully and classify all natural substances. With the few chemical tests established at that date this classification was mostly one on the lines of the old Assyrian method of grouping by external characteristics and (supposed) natural origin. Thus Andreas Libavius, like Agricola the metallurgist and mining expert, bothered little about theory but described chemical mani-

pulation and classification. In his *Alchymia* (1597) we find an exact description of the tools of the chemist and all operations such as calcination, sublimation, etc. He gave recipes for the preparation of a variety of products such as salts, amalgams, calces, etc., having defined chemistry as the 'art of perfecting magisteries (compound drugs) and extracting pure essences from mixed bodies by separation of their matters'. His classification of mineral substances such as bitumens, natural waxes, and resins shows ingenuity and clear observation and much of it still stands today.

This careful observation of the Paracelsan school led to the writing of a series of chemico–pharmaceutical handbooks, and hence we often speak of Iatrochemistry. The most important of these books are those of Nicaise Le Febvre of 1670 and Nicholas Lemery of 1677; they are the true ancestors of the modern text-books of practical chemistry. Of even more practical importance was the school which tried to understand the nature of the acids, salts, and alkalis with which the chemical technologist worked.

ACIDS, ALKALIS, AND SALTS

The first to attempt a rational explanation of their interaction was Otto Tachenius (1666) who held that many well-known industrial chemicals and minerals were compounds of acids and alkalis. His notions may have been ill-defined, as Boyle remarked, but when Rouelle introduced the concept of a salt being the compound of an acid and an alkali or base classification of these substances became more precise. The volatile alkali, 'ammonia', was already known; during the eighteenth century attention was focused on the 'fixed' alkalis. Pott and Marggraf separated the 'earth of alum' (alumina), which was found to be the alkali which formed alum with acids. In the years 1758–9 Ándreas Sigismund Marggraf succeeded in preparing a fixed alkali from common salt which he proved to be identical with mineral natron but different from the alkali contained in woodashes or tartar. Joseph Black then showed the difference between caustic and mild alkalis (1755), and this led to the proper understanding of the

nature of gases, since a gas ('fixed air', or carbon dioxide as we now call it) was 'fixed' in the mild alkali. Black's work is important as being essentially quantitative in character as contrasted with the qualitative approach then prevailing.

Towards the end of the eighteenth century when chemical technology was thriving after the discovery of many new processes for manufacturing such basic chemicals as sulphuric acid and soda further attention was given to the background of such processes. Such efforts led to certain advances in understanding the composition and properties of minerals and 'earths', but some important reactions remained unexplained.

PHLOGISTON POSTPONES NEW CONCEPTS

The eighteenth century marks the period of a violent struggle between new chemical concepts and a last revival of ancient chemistry, the phlogiston theory, which seemed to give a ready explanation of many chemical phenomena. In 1669 Joachim Becher had formulated a theory in which an 'oily earth' (*terra pinguis*) was responsible for the combustibility of chemical compounds. Georg Ernst Stahl elaborated this theory into a broad conceptual scheme into which most of the chemical phenomena such as oxidation, respiration, combustion, and decomposition seemed to fit. A burning substance was believed to release 'phlogiston' (Becher's *terra pinguis*) and to form a 'stony' or 'glassy' calx after calcination. In the words of Conant, 'What could be more plausible than to assume that in each instance the ore, when heated with charcoal, took up a "metallizing" principle which conferred upon the earth the properties of a metal?' If one called this hypothetical substance 'phlogiston', an 'explanation' for metallurgy was at hand:

$$\underset{\text{(an oxide)}}{\text{Metallic ore}} + \underset{\text{(from charcoal)}}{\text{Phlogiston}} \longrightarrow \text{Metal}$$

The fact that charcoal would burn itself when heated indicated to the 'Phlogistonists' that phlogiston escaped in the process and became combined with the air. In general, substances that burned in air were said to be rich in phlogiston; the fact that combustion

soon ceased in an enclosed space was taken as clear-cut evidence that air had the capacity to absorb only a definite amount of phlogiston. When air had become completely phlogisticated it would no longer serve to support combustion of any material, neither would a metal heated in it yield a calx; nor could phlogisticated air support life, for the role of air in respiration was to remove the phlogiston from the body. Everything fitted together well.

By 1740 this theory was generally accepted in France; ten years later it had become the orthodox theory of chemistry. However, the Arabs had stated that metals increased in weight on calcination. Jean Rey and the Royal Society in 1660 agreed with this. Other facts brought to light soon forced the phlogistonists to invent *prima facie* proofs and even confer 'levity' or a negative weight to their element phlogiston!

This change came about by the study of gases or pneumatic chemistry. Johan Baptist Van Helmont (1577–1644) had created the term 'gas' and had described different gases, but the eighteenth-century chemists created the means of generating, capturing, and analysing gases. Joseph Black introduced mercury as the liquid over which gases should be stored instead of the water mostly used up to that date (1750) and Joseph Priestley designed most of the apparatus which allowed the proper analysis of these simple substances. Thus Black prepared 'fixed air' (carbon dioxide) and learned how to detect it with lime. Henry Cavendish (1731–1810) learned to produce this gas from marble and acids and he also produced the first 'inflammable air' (hydrogen). Priestley experimented with 'phlogisticated nitrous air' (nitrous oxide, N_2O) and Carl Wilhelm Scheele succeeded in producing 'fire air' (oxygen) before 1773 and asserted that air was not, as was usually accepted, a simple substance but a mixture of two gases, oxygen and nitrogen.

In the meantime Antoine Lavoisier had experimented with sulphur and phosphorus (1772) and had noted that a 'prodigious quantity of air was fixed'. What the nature of this air was he did not investigate, as he was largely repeating Black and Priestley's experiments.

THE NATURE OF OXYGEN

The crucial point, the discovery of the nature of oxygen, was reached in the years 1774–8. Lavoisier started to experiment with red oxide of mercury, which just decomposes when heated alone below red heat, can easily be prepared from carbonate, and is formed when mercury is heated in air. In February 1774 Pierre Bayen noticed that red oxide of mercury when heated gives mercury plus a gas which he identified wrongly as 'fixed air' (carbon dioxide). In August of the same year Priestley repeated the experiment and held the gas to be 'diminished nitrous air' (nitrous oxide) which he already knew. Two months later he told Lavoisier of this experiment and he repeated it and made the same mistake which he even laid down in the so-called 'Easter Memoir' of 1775 read to the French Academy of Sciences. He introduced a valuable item in the experiment by carefully checking the weight of the original materials and those obtained by the reaction. This was the first step towards the new quantitative chemistry, which is practised according to what is now known as the Law of the Conservation of Mass.

Priestley on reading Lavoisier's monograph hastened to correct the mistake (November 1775), for, in the meantime, he had himself prepared oxygen by heating the red oxide of mercury (March 1775), which he had now discovered not to be the 'dephlogisticated nitrous air' for which he had originally taken it. He now held it to be a type of air 'at least as good as common air if not better', though he wondered how it was possible to obtain air which contained less phlogiston than common air. Priestley still clung to the phlogiston theory and could not shake himself free from it, even when he was practically its only adherent at the time of his death (1804).

Lavoisier, however, reading Priestley's remarks repeated his experiments and went further by preparing mercuric oxide from the metal, again carefully checking the weights before and after the reaction and realizing that this oxide was a true calx like any metal oxide. Further experiments convinced him that the prin-

ciple combining with metals during calcination was 'an eminently respirable air' (oxygen). When, in May 1777, Lavoisier read a memoir on the respiration of animals to the French Academy his ideas about oxygen were clear. He understood that air was not, as was always considered until then, a simple substance, but a mixture of oxygen and another gas which did not further combustion and which some came to call 'mephitic air', but which Lavoisier named 'azote' (nitrogen). In 1778 he published a revised edition of his Easter Memoir in which the early mistake about 'nitrous air' had been corrected.

THE COMPOSITION OF WATER

The years 1782 and 1783 saw the downfall of the old theory that water was an element. It was discovered that water was composed of about eight parts of oxygen and one part (by weight) of hydrogen. If mixed in this proportion an electric spark would detonate the mixture and water was formed. On the other hand, steam could be made to react with certain metals at high temperatures decomposing into hydrogen and the calx of the metal. It was clear that water was a compound of oxygen and hydrogen.

James Watt, Priestley, Cavendish, and Lavoisier were among the first to establish this truth, but their interpretation was by no means the same. Lavoisier, who by now had read Scheele's independent discovery (made well before 1773, but not published until 1775!), of 'fire-air' (oxygen), was convinced by experiment that the interpretation that hydrogen burned in air formed water was correct. The experiments of Cavendish were found to be correct. Hence Lavoisier published his *Réflexions sur le phlogistique* (*Reflections on Phlogiston*, 1783) showing that this concept was both unnecessary and self-contradictory. Priestley, modifying the original phlogiston theory, tried to make it fit the new facts and he even published a *Doctrine of Phlogiston Established and the Composition of Water Refuted* (1800). However, Lavoisier won the day. Black declared himself convinced by his theory and taught it at his lectures in Edinburgh. In 1782

Louis-Bernard, Baron Guyton de Morveau, proposed a tentative terminology, which Lavoisier published in an amended form in his *Traité élémentaire de chimie* of 1789. No longer were chemical compounds to be called by fancy names, although these still linger on in the terms used by pharmacists, but they were to be indicated by terms explaining their composition. Thus the gas formed by burning sulphur was to be called 'sulphur dioxide', 'oil of vitriol' was to become 'sulphuric acid', and the salts formed by it, 'sulphates'. The compounds of metals and oxygen were to be 'oxides', which with water formed 'bases'. This clear way of embodying facts in a good and systematic nomenclature made the destruction of the phlogiston theory inevitable. Lavoisier compiled a list of thirty-one elements which astonished many of his contemporaries though it was to be rapidly extended by the research of the next generation. Lavoisier continued to include 'light' and 'heat' as elements, the existence of which was soon denied, and eight of his elements were shown later to be compounds. However, Sir Humphry Davy by passing an electric current through certain bases was able to isolate sodium, potassium, barium, strontium, and calcium in 1807. Gay-Lussac prepared boron and silicon in 1809, and Wöhler, aluminium in 1827.

Chlorine, already prepared by Scheele in 1774, was recognized as an element by Davy in 1810. Iodine was obtained by Courtois in 1811, bromine by Balard in 1826.

ATOMS AND MOLECULES

Next came the solution of the question 'What are chemical compounds?' Were they just mixtures of simple substances (elements) or were they combinations? Did the characteristics of the atoms survive in the new molecules? Did the atoms combine in certain given proportions or indiscriminately? The solution of these problems led to the modern atomic-molecular theory.

As early as 1789, William Higgins had published his *Comparative View of the Phlogistic and Antiphlogistic Theories* in which he supported Lavoisier. He maintained that the molecules of chemi-

cal compounds were combinations of atoms of the constituent elements and he even suggested that they might combine only in certain given proportions of weights. John Dalton, investigating the physical behaviour of mixtures of gases and their solubility in liquids, was led to a similar theory based on a philosophical atomism. The conclusions of a paper read in 1803 and 1805 were elaborated in a series of lectures to the Royal Institution (1810). His principal work was his *New System of Chemical Philosophy*, the part most important for the history of the atoms being Vol. 1, Part I, of 1808. Though he held that the same volume of different gases contained different numbers of 'particles' (because they differed in size) he focused attention on the weight relations of the ultimate particles and said that atom-to-atom linkage was the basis of chemical combination, not the physical solution of many particles of one kind in a multitude of particles of another kind.

Dalton thus made weight the keystone of his atomic theory and in fact he had already appended a 'Table of the relative weights of the ultimate particles of gaseous and other bodies' (we would say atomic weights) to his paper of 1803. He also postulated the arbitrary rule that such atoms combined in simple proportions which he called the 'rule of greatest simplicity'. As well as this he developed a simple series of symbols for the representation of atoms and their combinations which, though now replaced by more serviceable ones, did not fail to simplify the discussion of these problems.

Other chemists had already hit on such ideas and were discussing them violently. Claude Louis Berthollet has shown in his *Recherches sur les lois de l'affinité* (1798) that the direction in which a reaction takes place may be altered by varying the proportions of the reagents. However, Berthollet was led into confusing homogeneous mixtures and chemical compounds, stating, for instance, that copper, on calcination, would yield copper oxides with progressively variable colours and weight proportions. This statement was violently disputed by Joseph Louis Proust who maintained that this series of copper compounds were just variable mixtures of two oxides of copper each of invariant composition. He denied that alloys, amalgams, and glasses were

chemical compounds at all, for a chemical compound is subject to 'a balance which, subject to the decrees of nature, regulates even in our laboratories the ratios of compounds'.

By the time Dalton proposed his theory many more chemists had joined in the fray and accumulated analytical data which, even given the relative inaccuracy of the prevalent analytic methods, confirmed Proust's views. Thus the German Jeremias Benjamin Richter had published a series of papers (1792–1802) on the combination (neutralization) of acids and bases. He formulated a 'law of equivalent proportions', which may be paraphrased as follows: If, for any two substances, there are certain weights which are equivalent in their capacity for reaction with some third substance, the ratio of such weights is the same regardless of what the third substance may be and, in doing so, confirmed Dalton's atomic hypothesis.

The fact that the relative weights of the combining atoms, the atomic weights, were the fundamental units of chemical science was clearly seen by Jöns Jakob Berzelius, the Swedish chemist who was probably the most precise chemist of his time. He wrote to Dalton: 'the theory of multiple proportions is a mystery but for the Atomic Hypothesis and, as far as I have been able to judge, all results so far obtained have contributed to justify this hypothesis' (1813). Berzelius took two important steps. First of all he introduced a new set of chemical symbols using the initial letters of the names of the elements instead of the circular symbols of Dalton (1813–14). Secondly he devoted many years of his life to the determination of the 'combining weights' or 'equivalents' of some 2000 elements and compounds which he published in 1818.

OBSTACLES AND ACCEPTANCE

In the meantime Joseph Louis Gay-Lussac had discovered in 1809 the law of combination of gases by volume, which can be expressed thus: Gases combine with one another in the ratio of whole numbers, and generally small whole numbers; and the volume of the product, if gaseous, bears a simple ratio to the

volumes of the reacting gases. Confusion arose as many did not perceive that Gay-Lussac spoke of parts by volume while Dalton meant parts by weight. Dalton concluded that Gay-Lussac's results suggested that equal volumes of different gases must contain the same (or simply related) numbers of atoms, but it seemed to him that his own results indicated that this was not correct.

The Italian physicist Amadeo Avogadro tried in 1811 to reconcile the atomic theory and Gay-Lussac's law of combining volumes. Carefully defining the particles such as atoms, molecules, and constituents of molecules under discussion, he suggested that the differences between the two schools of thought could be understood if we supposed that the particles in the gaseous elements did not consist of individual atoms but of molecules of such elements, each molecule consisting of a specified group of atoms. Hence a distinction should be made between the physically 'smallest particle' (the molecule of an element) and the chemically 'smallest particle' (the atom of the element). This postulate of poly-atomic molecules of the elements could not be accepted, as it seemed to contradict the chemical investigations of Davy and Berzelius.

The decomposition of compounds by an electric current by inserting two electrodes into a substance or its solution yielded a product of decomposition on each electrode. In the case of water these were oxygen and hydrogen. The fact that these two products carried an equal charge of electricity seemed to many a logical proof that chemical affinity and combination was due to the juxtaposition of positively and negatively charged bodies. On such facts Berzelius based his Dualistic Theory (1819), which was accepted by many chemists. Berzelius could not accept Avogadro's suggestion, and his combining weights left him only the possibility of suggesting a certain atomic weight from the several possibilities to which his results led him.

Matters became even more complicated when Petit and Dulong published a paper in 1819 interlinking the atomic theory with the theory of heat and stating that the product of the atomic weight and the specific heat of an element is 6·0, which empirical formula in many cases helped to select the proper atomic weight from the

figures deduced from Berzelius's accurate combining weights but failed in certain cases. However, further difficulties arose from Jean Baptiste Dumas' measurements of the vapour densities of gases at high temperature (1827) which allowed the study of the behaviour of gaseous mercury, sulphur, and such substances which were not among those gases usually studied at room temperature. Dumas started out from the idea 'equal volumes – equal numbers of particles', but his results conflicted with those obtained from other sources, for both he and Berzelius did not admit the possibility of poly-atomic molecules in gases and took the gaseous particles to be atoms. If, however, Dumas had assumed that his gaseous mercury molecule contained two atoms and that of sulphur six atoms, his results would have coincided with the other data.

For the time being the atomic theory seemed doomed while conflicting and varying atomic weights and molecular formulae calculated from these atomic weights and the determined combining weights appeared in the literature published between 1827 and 1858. Nevertheless, in the period between 1843 and 1856 Gerhardt and Laurent proved that the regularities in the vapour density figures of many compounds then tested could only be explained if simple relations such as that derived from the 'equal volume – equal number' idea were assumed. This was confirmed by the kinetic theory of the physicist which had been elaborated in the meantime. As other phenomena had gradually led to the rejection of Berzelius's Dualistic Theory a revision of the atomic weights adopted by him could be attempted. Evidence had also accumulated that, in certain cases, poly-atomic molecules did exist in elements in the gaseous state.

The confusion caused by different series of atomic weights and molecular formulae was finally cleared up by the Italian chemist, Stanislao Cannizzaro, who, in his *Sunto di un corso di filosofia chimica* (*Sketch of a Course of Chemical Philosophy*, 1858), returned to Avogadro's paper. 'We are to assume', he said, 'that the number of particles in equal volumes of all elementary and compound gases are equal. We should not confuse such particles with the atoms of which they are composed, though in

certain cases they may well consist of single atoms. We cannot expect to find equal numbers of atoms in equal volumes of elementary gases. However, important conclusions could be drawn from the comparison of the densities of the gaseous compounds of the elements. In the case of one specific element one then finds that all the weights of such an element present in equal volumes of its gaseous compounds prove to be integral multiples of one minimum value. This minimum weight should lead us to the correct atomic weight of any element in the prevailing system in which the atomic weight of hydrogen was taken to be the unit.'

Applying this reasoning, Cannizzaro proved that the 'Petit-Dulong values' and the 'vapour-density data' were concordant and that a consistent system of atomic weights could be drawn up. Soon afterwards most chemists accepted his results and Dalton's wish that the 'relative weights of the ultimate particles of both simple and compound bodies' be established was now realized very quickly as a result of the abundant analytic material already collected and now correctly interpreted. The atomic–molecular theory was finally vindicated.

CHAPTER 14

Isaac Newton

TOWARDS the end of the seventeenth century the principal lines along which natural science had developed since the middle of the sixteenth century converged in the dominating figure of Isaac Newton (1642–1727), in whom the transition from ancient–medieval to what was then called modern and is now referred to as classical science is definitely effected. From a review of this development three such lines emerge each of which, recapitulating the preceding Chapters 10–12, we can identify by its most prominent figures:

(*a*) Astronomy: Copernicus, Tycho Brahe, Kepler, Galileo, Huygens.
(*b*) Mechanics: Stevin, Galileo, Huygens.
(*c*) Optics: Galileo, Kepler, Descartes, Huygens.

The predominant method of studying nature in this period can be defined as mechanistic. This word should be understood to mean that explanations of natural phenomena are not regarded as sound unless they are based on hypotheses of form, size, position, arrangement, and motion of corpuscles which are subject to no other influences than those experienced through contact with other particles. The exponents of this mode of studying natural processes were Descartes, Gassendi, Boyle, and Huygens.

Newton's share in the development of science can be summarized as follows:

(1) He founded mechanics as an independent science by basing it on its own axiomatic foundation;
(2) He showed how to apply it to various fields of natural science;
(3) He established the definite synthesis of earthly and heavenly physics by relating mechanics to theoretical astronomy;

(4) He broke new ground for both the theory and practice of optics;

(5) He imparted a new meaning to the concept of mechanistic natural science;

(6) Through all this he created new possibilities for the whole field of natural science, the realization of which has continued without interruption to the present day.

All these achievements are incorporated in two books: *Philosophiae naturalis principia mathematica* (*Mathematical Principles of Natural Philosophy*, 1687) and *Opticks* (1704). His most decisive discoveries were not, however, made in these years. There are reasons to assume that this mainly took place in 1665–7, during which time Newton also conceived the fundamental ideas of his contributions to the creation of the calculus. We shall first ascertain from his writings what his scientific achievements were and then discuss any questions relating to their evolution and the share possibly to be assigned to others.

The three books of the *Principia* are prefixed by an introductory chapter in which, in the Euclidean manner, mechanics (in the sense of doctrine of motion) is logically constructed on definitions and axioms. The two groups of fundamentals are fully reproduced here because of their great historical importance. The English text is taken from Andrew Motte's English edition of 1729 of the *Principia*, which was re-edited by Florian Cajori and published by the University of California Press in 1934.

DEFINITIONS

Definition I: *The quantity of matter is the measure of the same, arising from its density and bulk conjointly.*

This quantity is also called body or mass. Expressed algebraically, $m = vd$ (m = mass, v = volume, d = density.)

The question arises whether this is a *circulus in definiendo*, density being nothing but mass per unit of volume. The answer is that Newton did not in the first place ask how d can be measured, as a modern physicist would do. He tried to express what

he saw as its essence: the degree to which the volume of a body is filled with matter (as distinct from void).

The mass of a body is measured by its weight which is proportional to it, as had been proved by pendulum experiments to be discussed later.

Definition II: *The quantity of motion is the measure of the same, arising from the velocity and quantity of matter conjointly.*

Algebraically, $I = mv$

if the quantity of motion, now called momentum, is represented by I (of impulse).

He generally referred to it as motion. It should therefore be borne in mind that with Newton:

$$\text{body} = \text{mass}$$
$$\text{motion} = \text{momentum}$$

He gave the expression

$$I = \Sigma\, mv$$

for a collection of points, in which he seems to have regarded v, i and I as vectors. The expression should therefore, even more anachronistically, be written as:

$$\bar{I} = \Sigma\, m\bar{v}$$

Definition III: *The vis insita, or innate force of matter, is a power of resisting, by which every body, as much as in it lies, continues in its present state, whether it be of rest, or of moving uniformly forwards in a right line.*

This is, of course, only seemingly a nominal definition. In point of fact it anticipates the principle of inertia to be formulated in Law I. The *vis insita* described is called *vis inertiae* (force of inertia) or *force of inactivity*, and is proportional to mass. It only operates when another force acting on the body tries to alter its state. It acts as a resistance to such a force, but also as an impulse insofar as it tries to alter the state of the body exerting the force.

Definition IV: *An impressed force is an action exerted on a body, in order to change its state, either of rest, or of uniform motion in a right line.*

'This force consists in the action only, and remains no longer in the body, when the action is over. For a body maintains every

new state it acquires, by its inertia only. Impressed forces are of different origins, as from percussion, from pressure, from centripetal force.'

Definition V*: A centripetal force is that by which bodies are drawn or impelled, or any way tend, towards a point as to a centre.*

The usual name is now central force. It should be observed that the idea of an attraction exerted by a centrum of force does not in the least prevail – as it will do in its subsequent development – over that of impulse, propensity, or tendency towards a centre. In the comment on Definition VIII Newton emphatically states that he will use these three terms *promiscue*, 'considering those forces not physically, but mathematically: wherefore the reader is not to imagine that by those words I anywhere take upon me to define the kind, or the manner of any action, the causes or the physical reason thereof, or that I attribute forces, in a true and physical sense, to certain centres (which are only mathematical points); when at any time I happen to speak of centres as attracting, or as endued with attractive powers.' He does not regard forces as physical realities but as means of mathematical description.

Definitions VI–VIII each define a quantity of a centripetal force.

Definition VI*: The absolute quantity of a centripetal force is the measure of the same, proportional to the efficacy of the cause that propagates it from the centre, through the spaces round about.*

Example: In the field of a magnetic pole, the quantity of magnetism in the pole.

Definition VII*: The accelerative quantity of a centripetal force is the measure of the same, proportional to the velocity which it generates in a given time.*

This is the intensity of the field at a given point; for the gravitational field it is the acceleration of a free-falling body. It is evidently implicit in this definition that under the influence of a force a point acquires a velocity increasing proportional with time.

Definition VIII*: The motive quantity of a centripetal force is the*

measure of the same, proportional to the motion, which it generates in a given time.

Thus if the accelerative quantity is a, the motive quantity is ma.

It should be observed that of the three different quantities only the accelerative quantity is used, being referred to as force, and that the concepts introduced, although exclusively defined for centripetal forces, are also applied to other forces.

The definitions are followed by a Scholium, in which Newton introduced the concepts absolute (or true and mathematical) and relative (or apparent and vulgar) time, absolute and relative space, absolute and relative place, and absolute and relative motion.

AXIOMS, OR LAWS OF MOTION

Law I: *Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.*

This is illustrated with examples.

(*i*) Projectiles continue in their motion until retarded by air resistance and pulled down by gravity.

(*ii*) A turning wheel does not stop rotating as long as it is not retarded by air resistance.

(*iii*) Planets and comets maintain both their progressive and their revolving motion longer in spaces that offer less resistance.

None of these three examples are convincing. *i* and *iii* can certainly not be verified empirically and in *ii* any maintenance of uniform rectilinear motion is out of the question.*

Law II: *The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.*

If the impressed force (to be regarded as an impulse) is I, this law can be read as the equivalent of

$$I = \Delta\,(mv)$$

Newton distinctly wrote of change and not of rate of change,

* (*ii*) is the reading in the second edition of the *Principia*; in the third edition, which was translated by Motte, (*ii*) deals with a spinning top.

so that there is no foundation whatever for the frequently heard assertion that Newton's Law II is equivalent to the formula

$$F = \frac{d\ (mv)}{dt}$$

defining the effect of a continuous force. Moreover, the applications of Law I, explicitly show that it refers to impulses.

Law III: *To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*

The principle of action and reaction thus formulated is probably Newton's most personal contribution to the development of mechanics.

All the motions referred to in the axioms are evidently intended as absolute motions.

The three Laws of Motion are followed by some corollaries.

Corollary I: *A body acted on by two forces simultaneously will describe the diagonal of a parallelogram in the same time as it would describe the sides by those forces separately.*

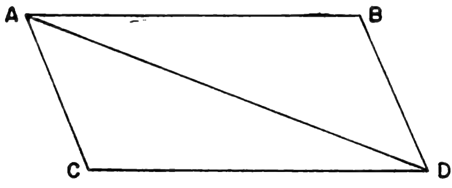


Fig. 18. Newton's parallelogram of impulsive forces.

Suppose (Fig. 18) that owing to an impulse M received in A a body would cover uniformly the distance AB in a time t, and also the distance AC due to the impulse N in A.

According to Law II neither impulse changes the effect of the other. Impulse M therefore brings the body on the line BD in time t; likewise impulse N brings it in the same time on the line CD. After time t it must therefore be on BD as well as on CD, thus in D. According to Law I it moves uniformly along AD.

Newton's reference to Law II shows that the statement later eventually formulated as the explicit axiom that the effect of a force is independent of the state of motion of the body on which it acts is considered by him to be implicit in the second axiom: the change in momentum of a body due to the action of a force takes place along the line of action of this force and is consequently independent of any motions. Newton's statement that under the influence of the first force the body would move uniformly from *A* to *B*, and the special reference to Law I to argue that under the influence of both forces it moves uniformly from *A* to *D* prove beyond doubt that he is thinking of impulses.

Corollary II deals with the composition and resolution of continuous forces in problems of statics. There is no logical connexion between the reasoning it contains and what precedes or follows.

Corollary III implies that the total momentum of a set of bodies cannot change by their action upon each other. All the velocities are assumed to be directed in parallel lines, and they must be put into positive or negative account according to the sense of their direction. If the velocities are not directed along parallel lines they are resolved into two directions.

Corollary IV expresses that the centre of gravity of a set of bodies subject to no other forces than those they exert on one another is at rest or in uniform rectilinear motion.

Corollary V contains the principle of relativity of classical mechanics already referred to in Chapter 12 (p. 211).

Corollary VI states that the mutual motions of a set of bodies do not change when all of them receive equal and parallel accelerations.

Newton stated in a Scholium that Galileo had derived the laws of falling bodies from the first two laws and the first two corollaries. This statement, which is in flat contradiction with all historical facts concerning Galileo, has long been maintained in historical literature. In the third edition of the *Principia* it is followed by a proof that *in vacuo* a constant gravity produces

a motion in which the distance covered is proportional to the square of the time; this reasoning does not occur in the first two editions.

In this Scholium and elsewhere Newton used the word force indiscriminately in two entirely different meanings: 'When a body is falling, the uniform force of its gravity acting equally, impresses, in equal intervals of time, equal forces upon that body; and in the whole time impresses a whole force and generates a whole velocity proportional to the time. And the spaces described in proportional times are as the product of the velocities and the times; that is, as the squares of the times.' He helped to maintain the endless confusion as regards the meaning of 'Force' which continued into the eighteenth and well into the nineteenth century. It sometimes means a force acting *on* a body and imparting an acceleration to it; sometimes something which a moving body possesses, the force *of* that body which is now something like momentum, now something like kinetic energy.

In extremely minute pendulum experiments (taking due account of the air resistance) he verifies the result of the collision theories of Wallis, Wren, and Huygens, in particular the theorem that a collision cannot change the relative velocity of two bodies with respect to each other. He introduces the restitution-coefficient for imperfectly elastic bodies.

Newton's foundation of classical mechanics has been represented here in greater detail than has been done with any other subject. This may be looked upon as a violation of true proportions and as such be disapproved of. It should, however, be borne in mind that the introductory chapter to the *Principia* is a document of fundamental historical importance which should be known to anyone who wishes to have some insight into the evolution of natural science.

The contents of the subsequent three books will, of course, be treated more summarily.

After an introductory mathematical treatise, to be reverted to in Chapter 15, Newton showed in Prop. 1 that a motion under the influence of a central force is subject to the Law of Areas, i.e. that the radius vector from the centrem of force to the moving

point describes mutually equal areas in mutually equal times. To this end the continuous central force is again conceived as a periodical impulse the period of which approaches zero; for the rest only Laws I and II are needed. Next, the way on which a force depends on the distance from the centre is derived for different cases of motion under the influence of a central force. For the special case of motion in an ellipse with the centrem of force in the focus (the case which according to Kepler's first law occurs in the motion of a planet around the sun) the force is in Prop. XI found to be inversely proportional to the square of the distance. The second law has already been found independently of the law of force; the third law is then proved for the special law of force of planetary motions.

It should be pointed out that Newton deduced from Kepler's first and second laws that the force acting on a planet in the direction of the sun is inversely proportional to the square of the planet's distance from the sun, but not conversely Kepler's first law from this law.

The rest of the first book is almost entirely devoted to planetary motion, but as in the case of the propositions mentioned above, all questions are framed and solved as mechanical problems. Thus, Prop. 61 contains a complete theory of the disturbances in the lunar motion without any mention of the word moon being made. In view of the origin of the *Principia* special mention should be made of Prop. 71–4, the gist of which is that when each particle of a homogeneous sphere exerts on a point outside the sphere a force which is inversely proportional to the square of the distance, the resulting force on the point is the same as if the whole mass of the sphere were concentrated in its centre.

Book II of the *Principia, The Motion of Bodies* (*in Resisting Mediums*), fully justifies the title of the work: it is a treatise on mathematical physics in general, without any direct relation to astronomy. Subjects dealt with in this book are: motions in resistant media with various assumptions as regards the dependence of the resistance on the velocity; hydrostatic and hydrodynamic problems, oscillating and undulating motion, circular motions of fluids. All these subjects were treated with great in-

genuity, but it is difficult for the modern reader to grasp the meaning on account of the absolute lack of analytical argumentation and because of the continuous use of infinitesimal magnitudes.

Book III. *The System of the World in Mathematical Treatment**, contains Newton's most spectacular achievement, the application of mechanics to cosmology based on the general theory of gravitation. The motions of the planets round the sun, of each of the planet's satellites round their central body, the earthly phenomena of motion of fall and projection and the tidal motions are all considered from a general point of view:

All bodies whatsoever are endowed with a principle of mutual gravitation.

Every two bodies gravitate towards each other in proportion to their masses and in inverse proportion to the squares of their distances. (Comment of Rule III of the *Rules of Reasoning in Philosophy* with which Book III begins).

In the special case of the moon this statement is verified quantitatively by ascertaining whether the moon's acceleration in its orbit round the earth and the acceleration of free-falling bodies are actually inversely proportional to the square of the distance moon–earth and of the earth's radius. There is no adequate foundation for the circumstantial and dramatic story that Newton was greatly excited by the fact that this verification failed at first and did not succeed until years afterwards. If any explanation has to be found for the delay in publication of the law of gravitation other than that accounted for by Newton's personality, in particular his aversion to promulgating his discoveries, it would be more obvious to think of the difficulties he seems to have been up against in finding the proof of Prop. I, 71–4. But there is not even a definite proof of any delay or postponement.

* This third book of the *Principia* should not be confused with *The System of the World, demonstrated in an easy and popular manner by the illustrious Sir Isaac Newton,* published in 1728 and intended for the general reader. It is incorporated in Cajori's edition referred to above and was probably written by Newton himself.

Prop. 7 contains the experimental proof of the axiom of the proportionality of mass and weight stated in the introduction. This is demonstrated by comparing the periods of oscillation of two equally long pendulums, the bodies of which are equally heavy but consist of different materials (wood and gold), while the air resistance is the same in both cases. No difference in period of oscillation was found.

Book III further describes various applications of the theory of gravitation in celestial mechanics which, like the theory of disturbance of the moon, are partly incorporated in Book I. Examples are the determination of a comet's orbit by three observations, the precession, the tides, and the flattening of the planets.

Fairly soon after Newton it became customary to speak of mutual attraction instead of mutual gravitation. This is hardly in keeping with his own conceptions. Although he occasionally used the word attraction, in accordance with his statement in the introductory chapter to the *Principia*, he preferred the neutral term gravitation which merely expresses what is known from experience, namely that the moon gravitates towards the earth and the planets gravitate towards the sun. This is not a hypothesis but an accomplished fact if Kepler's laws are accepted. The term attraction on the other hand already suggests a definite conception of the physical cause of gravitation while there is no evidence whatever to show why it should be preferred to impulsion, propensity, or tendency. As a matter of fact, the human mind seems to be partial to the idea of attraction. From of old it has been said that a magnet attracts a piece of iron, whereas all that is observed is that it moves towards the magnet.

The discussion of the *Principia* will now be concluded with some observations on the famous *Scholium Generale*, which forms the end of the book and in which the author slightly departed from the strictly scientific framework to which he has till then adhered. In the first place, it summarizes the arguments proving the untenability of the Cartesian vortex theory of planetary motions. This makes it clear why a separate Section (IX) of Book II is devoted to the circular motion of fluids. The

refutation of the vortex theory is obviously one of the main objects of the whole work.

Subsequently, it is argued that the structure of the solar system clearly points to the existence of a thinking Being who has arranged everything according to a fixed plan. Attention is called to the fact that all planets turn round the sun in the same direction in planes that practically coincide; to the great eccentricities of the comets' orbits which enable them to dart rapidly and easily among the planets, their velocity according to Kepler's second law being great in the vicinity of the sun; in the aphelia they move more slowly, but they are then much more distant from each other and therefore attract each other less. If the fixed stars are also central bodies of planetary systems these are also assembled according to the same plan and subjected to the power of One Being, who placed these stars at immense distances from each other to prevent them from falling on each other by their gravity.

Newton then discussed God's properties in detail. We know something of his attributes (qualities) from experience, but we know nothing of his substance (essence). This passage concludes with the characteristic words: 'And thus much concerning God; to discourse of whom from the appearances of things, does certainly belong to Natural Philosophy.'

The final passage is now quoted in full:

> Hitherto we have explained the phenomena of the heavens and of our sea by the power of gravity, but have not yet assigned the cause of this power. This is certain, that it must proceed from a cause that penetrates to the very centres of the sun and planets, without suffering the least diminution of its force; that operates not according to the quantity of the surfaces of the particles upon which it acts (as mechanical causes use to do), but according to the quantity of the solid matter which they contain, and propagates its virtue on all sides to immense distances, decreasing always as the inverse square of the distances. . . .
>
> But hitherto I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called a hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy.

In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction. Thus it was that the impenetrability, the mobility, and the impulsive forces of bodies, and the laws of motion and of gravitation, were discovered. And to us it is enough that gravity does really exist, and acts according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea.

And now we might add something concerning a certain most subtle spirit which pervades and lies hid in all gross bodies; by the force and action of which spirit the particles of the bodies attract one another at near distances and cohere, if contiguous; and electric bodies operate to greater distances, as well repelling as attracting the neighbouring corpuscles; and light is emitted, reflected, refracted, inflected, and heats bodies; and all sensation is excited, and the members of animal bodies move at the command of the will, namely, by the vibration of this spirit, mutually propagated along the solid filaments of the nerves, from the outward organs of sense to the brain, and from the brain into the muscles. But these are things that cannot be explained in few words, nor are we furnished with that sufficiency of experiments which is required to an accurate determination and demonstration of the laws by which this electric and elastic spirit operates.

This passage is of dual interest. It confirms once more Newton's statement in the introductory chapter of the work that he did not wish the forces referred to in the theory of gravitation to be conceived as physical realities but as means of mathematical description. But it also reveals that at heart he would have liked to exceed these limits of his principles and make natural phenomena also physically imaginable and comprehensible with the aid of ether hypotheses. However, in perfect agreement with Galileo's view pronounced in the *Discorsi*, he assigned the fulfilment of this task to the future.

The strict attitude assumed by him was understood by few. Although he emphatically rejected the idea that a body could exert an influence on another body across an empty space – which he considered to be absurd – he was reproached for assuming *actio in distans*. Two of his greatest contemporaries, Huygens and Leibniz, condemned the theory of gravitation as a relapse into the scholastic ideas of capacities and qualities and pro-

nounced the verdict, which they considered to be crushing, that gravitation was non-mechanical. It was certainly not mechanical in the sense attached to this word in the seventeenth century, when it only denoted contact effect between corpuscles. It could hardly be foreseen that little more than a century later Newton's theory of gravitation would be regarded as the prototype of a mechanistic view of nature and admired for this reason.

This change is of course not surprising to us. We know that 'mechanistic' means 'with the aid of mechanics'. The content of the first concept changes in accordance to the development of the second, so that two mechanistic views are not necessarily identical.

The appearance of Newton has been of immense importance for the development of science. Probably no single person has ever brought about such a radical renewal of natural philosophy as Newton did by setting up the theory of gravitation.

It is not surprising that the question has arisen as to whether the honour of this renewal actually accrues to him alone. During his lifetime this question was already answered in the negative by Robert Hooke, who claimed priority as regards the gravitation theory and the ensuing explanation of planetary motion. Some historians are now attaching more value to these claims than used to be the case. They point out that the excessive veneration in which the English have invariably held their great compatriot Newton threw Hooke into the background; they quote pronouncements of his which seem unmistakably to prove that an injustice is done to him by exclusively crediting Newton with the renovation of celestial mechanics. We mention as an example a passage from Hooke's treatise of 1674 entitled *An Attempt to prove the Annual Motion of the Earth from Observations*, in which he put forward the following propositions required for building up a doctrine of the universe :

1st, That all celestial bodies whatsoever, have an attraction or gravitating power towards their own centres, whereby they attract not only their own parts, and keep them from flying from them, as we may observe the earth to do, but that they also attract all the other celestial bodies that are within the sphere of their activity.

2nd, That all bodies whatsoever that are put into a direct simple motion, will so continue to move forward in a straight line till they are, by some other effectual powers, deflected and bent into a motion describing a circle, ellipsis, or some other more compound curve.

3rd, That these attractive powers are so much the more powerful in operating by how much the nearer the body wrought upon is to their own centres. But what these several degrees are I have not yet experimentally verified.

It can be imagined that a superficial reader of this passage will receive the impression that it essentially expresses everything discussed in Newton's *Principia* thirteen years later. More accurate reading however shows that the decisive, i.e. the quantative, element is lacking throughout.

Hooke certainly realized that the motion of a body having an initial velocity and subject to a force acting at an angle to this velocity can be conceived as the resultant of the motion of inertia and the motion effected by the force alone, but this surmise is a long way off from exact mathematical treatment. Nor is it sufficient to say that the force will probably increase with decreasing distance; what matters is the question how it changes. Hooke said that he had not experimentally verified this, evidently not realizing that what was needed at the time was mathematical reasoning rather than experiments, all the empirical material relating to planetary motion being comprised in Kepler's laws.

The tragedy about Hooke was that his pronounced experimental talents were not supplemented by mathematical capacities. In his opinion, these experimental talents compensate the lack of the latter and mathematical treatment is not fundamentally essential. This misconception has been maintained for a long time and has not even been fully abandoned in our time. There are still persons who think that the mathematical formulation and treatment of a physical theory is merely a matter of technique for which the aid of a mathematician is secured, but that the real value of an achievement lies in the fruitful idea and experimental investigation only.

Hooke must for certain eventually have understood that the force must of necessity be inversely proportional to the square

of the distance. This, however, was common knowledge of English scholars in the 1670s and it is easy to see how this was possible. They had at their disposal Kepler's third law and the formula stated in Huygens' *Horologium oscillatorium* of 1673 for the centripetal force required to make a point describe a circle uniformly. Now when a planet revolves round the sun in a circle with radius r, the following relations are valid:

according to Kepler $\quad \dfrac{r^3}{T^2} = C$

according to Huygens $\quad F = \dfrac{4\pi^2 r}{T^2}$

Eliminating T from these two relations we find

$$F = C\,\frac{4\pi^2}{r^2}$$

i.e. the force is inversely proportional to the square of the distance. This exclusively applies to a planet uniformly describing a circle with the sun as its centre. But Kepler's first law refers to an ellipse for which this simple deduction no longer holds good. Only Newton was able to cope with the mathematics of the general problem.

Although Hooke can certainly be credited with a share in establishing the theory of gravitation, it was not an essential share.

Newton made his principal discoveries in the field of optics, his second sphere of activity, also in the years 1665–7. There was no such delay in their publication as in that on mathematics and mechanics; in 1672 he communicated them to the Royal Society in a letter, *A New Theory on Light and Colours*. The criticism which came from various quarters annoyed him very much, and he was particularly vexed by the fact that Huygens showed little appreciation of his work. This experience certainly constituted one of the reasons why he afterwards showed so much reluctance to publish and often did not promulgate his discoveries until years after making them.

Newton's discoveries in the field of optics have now for a long

time been among the elementary subjects of this branch of science. This is conclusive evidence of their great importance.

They concern the colour dispersion of a narrow beam of parallel rays passing through a prism; the establishment that each separate colour is characterized by a specific value of the refractive index which increases from red to violet; the proof that the separate coloured rays are not dispersed once more when passing through a second prism; the synthesis of coloured rays to white light. This synthesis proves that white light not only comprises the various spectral colours, but that it consists of them.

Newton was perfectly aware of the slovenly way in which this was expressed. He pointed out that it is wrong to speak of red rays, etc., and that they should be called rubrifick or red-making rays. The rays themselves are not coloured any more than sound is present in a clock or in the air between a source of sound and the organ of hearing. But, adapting himself to the representation formed by laymen when they see the experiments, he continued to speak of coloured rays.

His discovery that refraction is always accompanied by dispersion gave Newton a clear insight into the enigmatic phenomenon of chromatic aberration of lenses which had worried all makers of telescopes. However, as a result of insufficient accurate observations, he believed that the dispersive power of the material from which a prism is made (i.e. the difference in refractive index for violet and red light) is proportional to the refractive index of the middle ray. This made him despair of the possibility of combining different types of glass to make achromatic lenses or prisms. He therefore applied himself to the construction of a reflecting telescope. Plans for such an instrument had already been proposed earlier and even attempts had been made by Niccolô Zucchi (1586–1670), Bonaventura Cavalieri (1598–1647), Mersenne, Descartes, and later by James Gregory. The latter's *Optica promota* of 1663 contains the description of a telescope in which the light of a celestial body is reflected by a large concave parabolic mirror, pierced in the centre, on to a smaller ellipsoidal concave mirror, which forms the final image in the middle of the central aperture of the large mirror. It is

observed there by means of an eye-piece. The system is reasonably free both of spherical aberration and only slightly affected by chromatic aberration. However, the manufacture of non-spherical mirrors involved great difficulties and Gregory gave up the project.

Newton was more successful as he demanded less of his mirrors. As an objective he used an ordinary concave spherical mirror, intercepted the image by a flat mirror at an angle of 45° to the main axis of the objective, and fitted the eye-piece in the side-wall of the tube. In 1672 this instrument was presented to the Royal Society, where it is still kept as a relic.

The *Opticks*, Newton's definite publication in 1704 of his investigations and discourses on optics, consisted of three books:

I. Geometric optics
II. Colours in thin sheets
III. Diffraction. Queries.

In *Opticks* Newton repeated his declaration of principles as regards hypotheses first stated in the *Principia*: 'Hypotheses are not to be regarded in Experimental Philosophy.' This time, however, this did not prevent him from making numerous conjectures as to the physical causes of optical and other phenomena and even partly propounding them as facts. Thus, in his explanation of what were afterwards called Newton's rings, he treated the alternate fits of easy transmission and easy reflection along a ray of light as experimentally established facts, which he then made use of.

The numerous explanatory hypotheses in the *Queries* are generally presented in an interrogative form: Do not . . . ? Is not . . . ? May not . . . ? Are not . . . ? Have not . . . ? This makes very unsatisfactory reading, because the author does not make the impression of standing up for his ideas, as is invariably the case with Descartes. It seems as if he had a bad conscience. This is not surprising at all: in his very daring, often even fantastic hypotheses he continually renounced his fundamental views of the task and method of natural science.

The result emerging from Newton's pronouncements on the

essence of light is that he adhered to a mixed corpuscular-vibratory theory. He sometimes referred to a current of flying particles, sometimes to the propagation of a vibration through ether. The latter idea enabled him to discuss the many phenomena of interference mentioned in his book. It would seem that he was most in favour of a theory of vibration, but his insurmountable objection to this theory is that he considered it incompatible with the fact of the rectilinear propagation of light.

The great success he had when assuming forces of attraction (not further explained in detail) in his theory of planetary motion led him to apply the same principle to the reflection and refraction of light. He assumed that when light particles in a less dense medium approach the boundary layer with a denser medium, this latter exercises a force at some distance perpendicular to the boundary plane and that this causes the partial reflection as well as the refraction in a way which we cannot discuss here in detail. As for Descartes, for him too the velocity of light is the larger the denser the medium is, and he, therefore, found the same law of refraction

$$n_{1,2} = \frac{\sin i_1}{\sin i_2} = \frac{V_2}{V_1}$$

Forces acting at a distance are also called in to explain the phenomenon of diffraction: the sharp edge of the obstacle placed in the way of a beam of light pulls the light particles out of their straight courses. Hence Newton called the phenomenon 'inflection'.

CHAPTER 15

Mathematics, the Handmaid of Science

MATHEMATICS AND NATURAL SCIENCE IN ANTIQUITY AND IN THE MIDDLE AGES

THE chronological order of our story is interrupted in this chapter to review the role hitherto played by mathematics in the development of natural science, so as to be better prepared for the part it will be seen to play later on.

When discussing Pythagoreanism in Chapter 2 we saw that the relationship between mathematics and science is as old as science itself. It was apparent in the relation between musical intervals and numbers and in the geometric treatment of celestial motions. This relationship was also largely maintained in Platonism. Wherever Pythagorean–Platonic ideas are subsequently encountered there is a distinct tendency to attribute a predominant influence on natural science to mathematical trends of thought and even to treat science as a sort of mathematics. A striking example of this is Archimedes' axiomatization of statics (p. 57) which has always been held to be a methodical prototype of mechanics, so that this subject has eventually come to be regarded as the prototype of natural science as a whole.

The mathematization of science was moreover encouraged by the Greek distinction between mathematical and physical astronomy and the fact that the former led to far greater successes than the latter. Astronomy was celestial geometry. It inspired Plato to his words *ὁ θέος ἀεὶ γεωμετρεῖ*, which for ages has remained the astronomers' motto.

The characteristic Greek conception of the relation between music and arithmetic on the one hand and between astronomy and geometry on the other is explicitly formulated in the motivation of the composition of the quadrivium given by Boethius. Things that have dimensions can be distinguished as (1) quantities (*πλήθη*) and (2) magnitudes (*μεγέθη*). The former can

be regarded (*a*) individually and (*b*) in their mutual relationship; the latter (*a*) at rest and (*b*) in motion.

1(*a*) takes place in arithmetic, 1(*b*) in music; 2(*a*) in geometry, 2(*b*) in astronomy. It is owing to him (he was not unjustly surnamed the teacher of scholasticism) that the Greek conception of the function of mathematics in natural science has from the start influenced Western culture, although its effect was not at first perceptible owing to the low level of mathematical development.

The respect in which Archimedes and Ptolemy were held in the Middle Ages, even by those who did not fully understand them, caused their procedures to be regarded as methodical ideals. We have already seen that in the fourteenth century the endeavour to treat natural phenomena mathematically was gaining ground. The results were meagre in the field of arithmetic; in the field of geometry there emerged the fruitful method of graphic representation.

MATHEMATICS AND NATURAL SCIENCE IN THE SEVENTEENTH CENTURY

With the approach of the flourishing period of natural science there was an increasing number of voices testifying to the essential importance of mathematical thinking. Although Cusanus's metaphysical argument that mathematics is the mirror revealing the highest truth for mankind or Leonardo's statement that mechanics is the paradise of mathematical sciences were not yet of real importance to the history of natural science, it is impossible to turn a deaf ear to the numerous, essentially agreeing, pronouncements of the greatest sixteenth and seventeenth-century exponents of natural science: Galileo, Kepler, Descartes.

Galileo's opinion on the function of mathematics in natural science is best expressed in his own words in *Il Saggiatore* (*The Assayer*):

Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letters in

which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures, without which it is humanly impossible to understand a single word of it; without these, one wanders about in a dark labyrinth.

The exclusively geometric formulation of this statement is not surprising: astronomy, the branch of science which had made the greatest progress in Galileo's time, was fully adapted to geometry; his own principal contribution, the theory of fall and projection, was in the majority of cases couched in geometric terms in view of the low degree of development of algebra. To give a single, simple example: when he wished to compare the times required by a free-falling body to cover two given distances OA_1 and OA_2 from the position of rest in O, he said that they are in the proportion of one distance to the mean proportional of both. He deduced this by applying Euclidean propositions from the fifth book of the *Elements* and, like any Euclidean proposition, it is entirely reasoned out in words. Today, denoting the two distances by s_1 and s_2 and the times by t_1 and t_2, we should write:

$$\begin{aligned} s_1 &= \tfrac{1}{2} g t_1^2 \\ s_2 &= \tfrac{1}{2} g t_2^2 \end{aligned} \qquad \text{thus} \quad \frac{t_1}{t_2} = \frac{\sqrt{s_1}}{\sqrt{s_2}} = \frac{s_1}{\sqrt{s_1 s_2}}$$

and read Galileo's proposition from these formulae. However, in the seventeenth century there was no question of algebraic formulae expressing the relation between physical magnitudes, and the above deduction, which is so obvious to us, would have been incomprehensible in Galileo's time.

The essential relation between mathematics and natural science is expressed even more clearly by Kepler than by Galileo. Adopting the idea underlying Plato's *Timaeus*, he advanced as the fundamental proposition of his cosmology that God, in creating the world, allowed himself to be guided by mathematical considerations, aiming at certain λόγοι κοσμοποιητικοί, world-forming relations. At the same time, however, he created a human mind capable of discerning quantitative relations which, indeed, is its proper function. It was Kepler who said that,

just as the eye is adapted to seeing colour and the ear to hearing sounds, man's intelligence is *ad quanta intelligenda condita* (adapted to knowing quantities).

The human mind is God's immaterial, nature His material image. When a human being practises mathematics, he re-thinks God's thoughts which have been materialized in nature. This constitutes his capability of studying natural science. Just as for Plato, there was for Kepler an ideal world possessing a higher reality than the empirical world, its material expression, and also for him the function which empiricism has to fulfil in the investigation of nature consists in inducing us to acquire a knowledge which our mind already possesses in virtue of its divine origin.

Descartes was less ecstatic than Kepler as regards the relation between mathematics and natural science, but his conviction of its existence was no less deeply rooted. In his *Regulae ad directionem ingenii* (written in 1629) he developed a theory of studying science which essentially amounts to the argument that mathematical concepts and proofs can and must be applied to all earthly sciences. The point is always to observe the two great principles of *ordo* and *mensura*, *ordo* denoting an arrangement of propositions in deductive chains and *mensura* expressing the quantitative treatment.

With him this extremely mathematical state of mind was not, as in the case of Galileo and Kepler, compensated by an attitude of unconditional respect for experience. As a result, Descartes was often led astray, while on the other hand he was not able satisfactorily to work out the ideas of nature originating from his mathematical turn of mind. All the same, he greatly impelled the treatment of natural science in a mathematical direction. As has been explained above, the seed scattered by him has borne rich fruit, especially in the work of Huygens.

The immense influence of the ideas of these three great minds on the development of natural science in the seventeenth century is better realized in retrospect than it was by their contemporaries. The great progress achieved as the result of the harmonious cooperation between empirical investigation and mathematical systematization is noticeable in the hypothetico–deductive

method. This term does not occur in the seventeenth century since it is of a comparatively recent date. Nor is its equivalent, the *risolutivo–compositivo* method, ever heard of after Galileo. The terms in use are experimental method or experimental philosophy, which one-sidedly stress one of two inseparable components.

This is most probably a symptom of the powerful influence which Francis Bacon continued to exert on the philosophy of natural science throughout the seventeenth century and which was to be revived in the nineteenth century in the highly inadequate, yet generally accepted description of scientific method as being empirical–inductive. This term not only undervalues (through suppression) the merits of mathematics for natural science in the formulation of hypotheses and the deduction of consequences, but it also ignores the creative achievement of framing fruitful hypotheses. Bacon's basic idea of drawing up lists which would as it were automatically give rise to the creation of new views evidently still confused people's minds regarding the procedures adopted in natural science.

The essential importance of mathematics for science naturally leads us to expect a favourable influence of the progress made by mathematics in the seventeenth century on the development of science, while the question arises where and how this influence was effected. The expectation has been fulfilled, but the question as to where and how is not so easy to answer as one would be inclined to believe. The three greatest mathematical achievements of the age that come to the mind are symbolic algebra, analytic geometry, and calculus, the second being a fruit of the first and an indispensable element of the third. All three of them were undoubtedly of importance, but not in the manner which would at present seem to be the most obvious.

Symbolic algebra was almost solely applied indirectly, that is insofar as it occurred in analytic geometry and calculus. It was not yet employed for a shorter and more concise rendering of scientific arguments and it was not until the nineteenth century that it came to be used in what is now regarded as its most important function: the formation of formulae in which letters

expressing physical magnitudes in standard units are combined with due observance of their dimensions and subjected to calculations.

The current opinion that Newton and Leibniz were the first to devise the new branch of mathematics which was afterwards used in natural science under the name of calculus does not fit the facts. In this representation the actual facts are condensed beyond all recognition, its attractive simplicity being acquired at the expense of truth.

The invention of the calculus cannot be regarded as an isolated historical fact. The problems of integral calculus (determination of the lengths of curves, areas enclosed by curves, volumes enclosed by flat or curved surfaces, centres of gravity of geometric figures and bodies) had cropped up from Greek Antiquity onwards and had even been solved in many cases. Questions which were to give rise to differential calculus, in particular those referring to the extreme values of functions and tangents to curves, had been asked early in the seventeenth century and most of them had been answered. It was the great merit of Newton and Leibniz that they established a relationship between these two fields of mathematics, which had developed independently, by pointing out that the problems of integral calculus were the inverse of those of differential calculus; and that they introduced general notations and methods of computation for both. Only from that time onwards is the term calculus justifiable. But this does not mean that before that time there were no branches of mathematics dealing with the problems of calculus.

These branches certainly existed. The Greeks had already introduced the idea of what was later to be called the indivisibles in the field of integral calculus: a body was conceived to be the sum of its cross-sections with parallel plane surfaces; a plane figure the sum of parallel sections of line having no thickness; a line the sum of dimensionless points. Point, section of line, and plane were indivisible building stones of line, plane figures, body. The logical untenability of this representation did not hinder Archimedes from reaching important results with it, but in his

publications he refrained from showing that he had used it. After obtaining his results he proved them by the absolutely strict method introduced by Eudoxus for infinite processes which in its double *reductio ad absurdum* reached a degree of exactness in no way inferior to that of the nineteenth-century theory of limits.

In the seventeenth century the concept of infinitely small or infinitesimal was added to that of indivisible. A plane figure enclosed by curves was no longer solely conceived as the sum of parallel sections of line but also as the sum of an infinite number of infinitely narrow rectangles. This idea was logically just as untenable as that of the building-up of a continuum with a given number of dimensions from indivisibles having one dimension less, but the untenability has a different reason. Indivisibles (points, sections of lines, plane cross-sections) do exist, but it is incomprehensible how a continuum with one dimension more could be built up from them. Infinitesimals do not exist: a section of line has a length which may be zero or finite, but not something intermediate between zero and finite.

Working with infinitesimals was of no less importance for the development of seventeenth-century mathematical and natural sciences than the use of indivisibles. Mechanics in particular profited by it. Just as in mathematics reference was made to infinitely narrow rectangles which were no sections of line, mechanics referred to infinitely small distances which were no points and to infinitely small times that were no moments. There was no more need for students of mechanics to wait for the calculus than had been done in the numerous algebraic and geometric problems which at present could hardly be regarded as anything else than calculus problems.

In point of fact, calculus itself was at first one of the applications of what in a wider sense of the word than usual might be called the infinitesimal method.

To Leibniz a differential quotient was actually a quotient of two infinitely small magnitudes named differentials, while an integral was the sum of an infinite number of such infinitely small differentials.

AN APPLICATION OF INFINITESIMALS

We shall now give an example of the procedure of working with infinitely small magnitudes, choosing the way in which Newton proved the fundamental Prop. XI of the first book of the *Principia*, the proposition that a point describing a Kepler ellipse is acted upon by a force that is inversely proportional to the square of its distance from the centre of force. This proof is based on a general theorem on central motion (Prop. VI) stated here without its deduction.

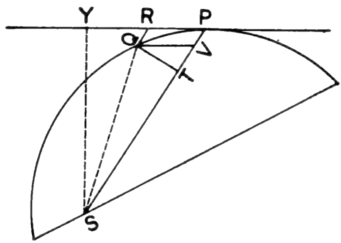


Fig. 19. Newton's *Principia* I, Prop. VI.

Let point P (Fig. 19) describe a curve under the influence of a force directed to the centre S. In an infinitely short time it describes the distance PQ. PR touches the curve in P. $QR//SP$, $QV//RP$, $QT \perp SP$. According to the proposition, the force is as

$$\frac{QR}{QT^2.PS^2}$$

The proof of Prop. XI is given as follows (Fig. 20):

$AB = 2a$ is the major axis of the ellipse described, $CD = b$ is half the minor axis. S and U are the foci, S being at the same time the centre of forces. The conjugate diameters G_1P ($= 2b_1$) and EE_1 ($= 2a_1$) pass through the centre C. EE_1 meets SP in L. The letters P, Q, R, V, T have the same meaning as in Fig. 20. When produced, QV intersects CP in W. $PF \perp CE$, $UM// CL$. CP being the acute bisectrix of $\angle$ SPU, and UM parallel to the

obtuse bisectrix PR, $PM = PU$, CS being $= CU$, $LM = LS$. Hence:

$$PL = \tfrac{1}{2}(PU + PS) = a$$

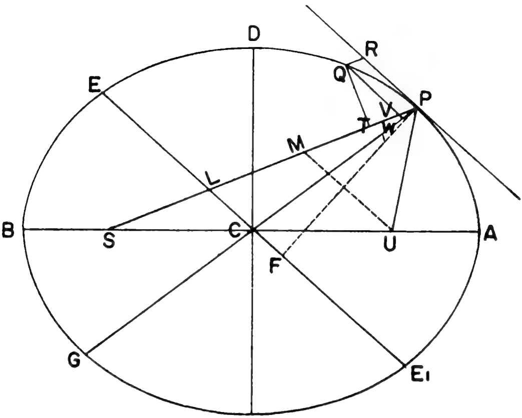


Fig. 20. Newton's *Principia* I, Prop. XI.

This introduction is followed by the proof proper: On account of the fundamental property of the ellipse in the classical theory of conic sections:

$$\frac{QW^2}{PW.GW} = \frac{a_1{}^2}{b_1{}^2} \qquad (1)$$

On account of similarity of $\triangle\, QTV$ and $\triangle\, PFL$ and as, according to a proposition of Apollonius:

$$a_1.PF = a.b$$

$$\frac{QT^2}{QV^2} = \frac{a^2b^2}{a_1{}^2a^2} = \frac{b^2}{a_1{}^2} \qquad (2)$$

Further, since $CL // VW$:

$$\frac{PW}{QR} = \frac{PW}{PV} = \frac{PC}{PL} = \frac{b_1}{a} \qquad (3)$$

Putting $QW = QV$ and $GW = GP$, it follows from (1), (2), and (3) that

$$\frac{QT^2}{2b_1.QR} = \frac{b_1^2}{b_1 a}$$

thus $$\frac{QT^2}{QR} = \frac{2b_1^2}{a} = O$$ (the orthia pleura or latus rectum of the ellipse)

According to Prop. VI, the force is as

$$\frac{QR}{QT^2.PS^2} = \frac{1}{O.PS^2}$$

thus inversely proportional to the square of the radius vector.

This proof of one of the most fundamental propositions of the *Principia* has been given here *in extenso*, not only to illustrate the working with infinitely small magnitudes, but also to bring up a general question concerning the whole work.

Newton's argumentation, which seems strange and difficult to the modern reader, has given rise to the surmise that he had found his results in a manner quite different from the way he published them. He is assumed to have used his new theory of fluxions but to have produced his reasoning in the traditional Euclidean style for fear that his deduction would be incomprehensible to contemporary readers who were not yet familiar with his new method.

It is very difficult to reconcile this opinion with the facts. In the first place, the reasoning outlined above is by no means Euclidean. It does not at all fit in with the framework of Greek mathematics, from which it would undoubtedly have been debarred as being far too inexact. The method underlying the whole work must also have been absolutely new to most of Newton's contemporaries. In addition, nobody has ever even made an attempt at demonstrating Prop. XI by means of the conceptions and propositions of the theory of fluxions known at the time. It is indeed very difficult to see how this could have been done, in view of the level the calculus had then reached.

Moreover, Newton *does* raise the subject of his new calculation of fluxions and indeed uses it in his deductions, namely in Prop. VII of Book II of his *Principia*. Why then should he studiously have avoided it in other places?

The relation between mathematics and natural science is not always the same to Newton as it is to us. For instance, it is often self-evidently assumed that one of the origins of the concept of fluxions was the desire for an accurate definition of the concept instantaneous velocity of a variable motion. This is an obvious idea for a modern mathematician, because he uses the question: 'What is to be understood by instantaneous velocity?' as a means of explaining the concept differential quotient to beginners. This is by no means the case with Newton – on the contrary, he based the concept of fluxion on the concept of instantaneous velocity, which he regarded as being clear by intuition. The fluxion of a fluent regarded as a function of time is its rate of change, and not vice versa.

This chapter will be concluded with the remark that the increasing application of the infinitesimal method in seventeenth-century mechanics has led to a weakening of the requirements of mathematical exactness traditionally inherent in Greek mathematics. Galileo was strictly Euclidean in his *Discorsi*. Torricelli, although at first following his example, soon began to use indivisibles and infinitesimals. Kepler discarded Greek rigorousness right from the outset. Huygens freely used the great heuristic possibilities afforded by the infinitesimal method, but in his publications he felt obliged to adhere to the Greek style. Hence the marked difference between the manner in which he had deduced his famous proposition of the tautochronism of the cycloidal motion of falling and that in which he proved it in his *Horologium oscillatorium*. Gradually, however, it became far too difficult to maintain this distinction and in the end he abandoned it. There are indications that he did not do so without an inner struggle.

Newton seems to have been up against the same dilemma. The first book of the *Principia* opens with a mathematical chapter entitled: 'The Method of First and Last Ratios of Quantities'

and containing a number of propositions which together form a theory of limits. He arrived at formulations which closely approximate those of nineteenth-century mathematics. However, as soon as he started upon his work proper, the development of mechanics, there is very little evidence of the introductory chapter.

The relinquishment of the old requirements of stringency has no doubt considerably expanded the possibilities for both mathematics and mathematical physics and greatly stimulated their development. When, however, early in the nineteenth century mathematicians returned to the early conceptions of exactness and made the requirements even more stringent, the students of mechanics did not follow them in this respect. As a result, they were still using the infinitesimal in a manner which leaves much to be desired from a mathematical point of view.

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THIS bibliography is far from complete. It is restricted to the reliable handbooks or special treatises which can be consulted with profit to deepen the knowledge gained by reading the different chapters of this book. In these recommended volumes the reader will himself be able to find sufficient indications for further reading. Dates given are of those editions consulted by the authors.

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